Academic year 2017-2019

STRATEGIC INTER-FOSSIL FUEL EFFECTS OF CLIMATE POLICIES:

A GAME-THEORETIC ANALYSIS

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Thesis submitted in partial fulfilment of the requirements for the joint academic degree of International Master of Science in Rural Development from Ghent University (Belgium), Agrocampus Ouest (France), Humboldt University of Berlin (Germany), Slovak University of Agriculture in Nitra (Slovakia), University of Pisa (Italy) and University of Córdoba (Spain) in collaboration with Can Tho University (Vietnam), China Agricultural University (China), Escuela Superior Politécnica del Litoral (Ecuador), Nanjing Agricultural University (China), University of Agricultural Science Bengaluru (India), University of Pretoria (South-Africa) and University of Arkansas (United States of America)

This thesis was elaborated and defended at Humboldt University within the framework of the European Erasmus Mundus Joint Master Degree "International Master of Science in Rural Development " (Course N° 2015 - 1700 / 001 - 001)

Certification

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Preface:

The inspiration for writing this paper originates from the research project: “Aligning Mitigation Targets with Incentives of Fossil Fuel Producers: Inter-Fossil Fuel Effects” conducted at the Humboldt University by Prof. Dr. Klaus Eisenack, Dr. Achim Hagen and Dr. Roman Mendelevitch. During my master degree study with them, their expertise inspired my interest for game theory models, which drove me to participate in further research in this field.

In truth, I couldn’t have achieved my current research results without the support of all my promoters mentioned above. Besides, I also would like to thank my parents and friends for their love and understanding.

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1 Abstract:

Climate coalition between different individual countries demonstrates positive potential in resolving climate change problem since Paris Agreement. In this paper, attention is drawn to interaction between different fossil fuel producers and country governments by implementing supply-side policy in a global environment. A three-stage game theory model is created to analyse especially the inter-fossil fuel effects. Analytical results from the second stage show the interaction relationships between taxes in different countries. Other variables, such as environmental damage factor, usually together with different emissions intensity settings also influence the tax level. Later in the first stage, numerical model shows, that besides Nash Equilibrium, where no coalition is formed, there might also exist another Nash Equilibrium, where a small coalition is formed between two cleaner oil and gas countries. Besides, potential external and internal stability of grand global coalition case is also proved to exist, even when other Nash Equilibrium is reached, and therefore less emission is actually possible.

2 Introduction:

Climate policy that sets carbon mitigation targets through international collaboration process might be a possible resolution to the global warming issue. Problems such as carbon leakages or free-riding however still exist, and act as major drawbacks to the desired progress. Extensive research has been done so far to illustrate the complexity of international climate policy and propose possible solution models, e.g. climate clubs (Nordhaus, 2015), model based on moral incentive (Collier & Venables, 2014). Policy instruments lie in both demand and supply side, but the application scenario can be quite diversified.

Carbon leakage exists where carbon emissions abatement in a group of countries result in increased emission in non-abating countries. The traditional policy instruments usually focus on the demand side, for example, carbon consumption tax. If it is implemented within a coalition, demand for fossil fuel is reduced. Then the world price for fuel declines and so the non-participating countries consume more. Carbon leakage also exists when supply side policy is implemented. If a country within a coalition decides to shrink their supply, it will encourage the non-participating countries to supply more. The Kyoto protocol calls for a group of countries to limit their carbon emission while the other countries, that have no abatement commitments, actually could emit more. Several studies prove that this may lead to a leakage rate as high as 10 percent (Paltsev, 2001). Binding commitments under Kyoto were estimated to have increased committed countries' embodied carbon imports from non-committed countries by around 8%, and the emission intensity of their imports by about 3% (Kuik & Gerlagh, n.d.; Rahel & Gabriel J, 2015). Therefore, carbon leakage exists quite often, and results in weakening the power of coalition's effective abatement.

Besides, free riding is also a key issue regarding non-rivalry and non-exclusiveness of public goods. In this case, carbon emission abatement is the benefit, which the countries are willing to receive at no cost of contribution, since no actor can be excluded from these benefits, regardless of their participation. Also the benefits of climate protection for one actor are not reduced if other actors benefit. Countries have high motivation to free-ride on carbon coalition and it becomes more and more difficult to induce countries to join in an international agreement with significant reductions in emissions. In the end, no stable climate coalition exists and emission abatements fail (Nordhaus, 2015).

Notwithstanding these drawbacks on international climate coalition, Paris agreement has demonstrated relative success by setting a clear globally agreed target to keep the increase of global mean temperature below 2 ℃ and striving for 1.5 ℃. It means a large share of current fossil fuel reserves will be refrained underground (Mcglade & Ekins, 2014). Fossil fuel producers can't generate as much profit as expected considering this constraint. Since different fossil fuel has different emission factors, for example, coal is much dirtier compared with gas, there may exist comparable advantage for cleaner energy in spite of their high prices when taking emission into general welfare consideration. So one possible driver of forming a climate coalition could be inter-fossil fuel effects, which means the possible substitution effect among the various fossil fuels (Stern, 2012).

In this paper, my motivation is to further analyse the impact of inter-fossil fuel effects on climate policy and interaction between different countries. For example, determine if an international climate coalition will be formed or not, and how can climate policies change production decisions and global emissions. Based on this, we will have a better understanding of the effects of climate policy design on the distribution of rents and resulting incentives.

Aware of carbon leakage issue from implementing either demand or supply side policy alone, there may exist possibility of combination of other strategic behaviour and policies. Recent studies from supply sides demonstrate outstanding results. It's proposed by Harstad in 2012 that the environmental coalition's best policy is to simply buy foreign deposits and conserve these. The coalition can then reduce its own supply marginally without fearing that non-participants will increase theirs. In this way, the coalition benefits from less carbon leakage (Harstad, 2012). Besides, researchers also made several extensions based on the three-stage model proposed by Harstad. For example, differentiation is made between deposit reservation policy and extended deposit (Eichner & Pethig, 2017). Welfare is analysed by comparing both scenarios. In another paper, Eichner & Pethig (2017c), they also made further extension of deposit market, where coalition can exert market power. Further, they investigated how the choice of climate policy instruments influences the conditions for the formation of stable and effective climate coalitions by combination of deposit purchase policy with other options, such as tax(Eichner & Pethig, 2017). However, inter-fossil fuel effects are still neglected here.

Fæhn et al. (2013) contributes to the theoretical literature by analysing how differences in emissions from fossil fuel extraction across countries affect the relative performance of demand side policies versus supply side policies and how domestic demand and supply side policies affect global emissions, contingent on market behaviour in the fossil fuel markets. Combined with costs of demand and supply side policies, they also prove that given a care for global emissions, the majority of emission reductions should come through supply side measures, i.e., by downscaling Norwegian oil extraction (Fæhn et al 2014). Here, inter-fossil fuel effects are studied within unilateral action, or more specifically, domestic policy. Furthermore, Hagem and Storrøsten (2016) find that a credible announcement of future unilateral supply-side policies reduces early foreign emissions and derive the optimal combination of consumer taxes and producer taxes when both spatial and inter-temporal leakages from the free-riders are taken into account. They further evaluated the combination of local polices considering carbon leakage, but here different fossil fuels are treated as an aggregated fuel.

Grey paradox, named by Coulomb and Henriet, implies a possible phenomenon where carbon taxation could increase the profits of owners of polluted fossil fuel under certain conditions. In the paper, it’s well studied how fossil-fuel owners can benefit from carbon taxation considering inter-fossil fuel effects with exogenous climate policies. In the model setting, a carbon ceiling is set and different fuels are included to analyse the role of resource endowments, pollution contingents, extraction costs and demand elasticities.

These fuels are differentiated by emission intensities, for example, one dirty but abundant fuel, one clean but expensive backstop, and an intermediate fuel. It shows under certain conditions the exhaustible-resource owners' profits increase as the ceiling is tightened (Coulomb & Henriet, 2018). Similar to this study, inter-fossil fuel effects will be discussed in my study also, however, climate policies are endogenized to study on countries' interaction behaviors. In this case, different carbon coalition might be formed and then stability of these coalitions will also be tested (Hagen, Altamirano, Juan, & Weikard, 2016; Hagen & Eisenack, 2019; Weikard, 2009).

Other ideas than demand and supply policy focus are also discussed. For example, Nordhaus studied the club as a model for international climate policy, where small trade penalties on non-participants can finally induce a large stable coalition with high levels of abatement (Nordhaus, 2015). What's neglected here is the possible fight back action against the coalition from non-participants, especially when their power is relatively big. In addition to this, another idea that combines this economic benefit and moral incentive could be a sequenced closure of the world coal industry with compensation from oil producers in the high-income countries to coal producers in the low-income countries(Collier & Venables, 2014). This actually fits with the reality nowadays, where high-income countries try to compensate others' loss to ensure a lower emission level. Behavioural economics also illustrate introduction of reciprocal preference into national climate negotiator level (Nyborg, 2018). It demonstrated the existence of a stable majority or grand coalition under certain conditions, which encourages a possible successful model like Paris agreement simply under voluntary pledges, even though the model is perceived obviously highly stylized.

In this paper, we continue to further study supply side policy with a focus on interaction between different fossil fuel producers and country governments in a global environmental policy negotiation position. We analyse how different governments regulate local climate policy by setting production tax and make a decision to join a coalition or not. To do so, our approach is to create a three-stage game theory model to better understand the effect of climate policy. Numerical models are also built to understand the analytical results. The rest of this paper is organized as follows: Section 3 introduces methodology of game theory model we use in the paper. In section 4, I will discuss the model assumptions and settings of the analysis. Results and further discussion are included in sections 5 and 6. Finally in conclusion part, I will also mention the limitations of the paper and recommendations for further research.

3 Methodology:

Game theory focuses on the study of mathematical models of conflict and cooperation between intelligent rational decision-makers (Myerson, R. B. 2013). It’s widely used for systematic analysis of strategic interactions. Historically, important applications of game theory include analysis of gambles and other games, planning of military operations, industrial organization, e.g. market leadership, bilateral monopoly. In International Environment Agreement studies, where each individual country is assumed to be an individual rational participant that makes decisions considering others’ reaction, game theory model so far demonstrates great explanatory and analytical power.

In game theory model, the basic setting usually includes different players, strategy spaces and payoff-functions in regard to strategy spaces. Each player aims to maximize their payoff considering others’ reactions. A Nash Equilibrium is a profile of strategies such that each player’s strategy is an optimal response to the other players’ strategies (Fudenberg, D. & Tirole, J. 1991). In this paper, we would assume different government is rational enough to make decision to maximize their own utility considering others’ reaction. In a Nash Equilibrium where no country has other incentive or motivation to change their decision, it could be considered stable. For example, if some countries consider to form and join a coalition and work jointly to limit carbon emission, no more other countries want to join to increase their own benefit and at the same time no countries inside the coalition want to quit, we could say a Nash Equilibrium is reached. However, there also exists case where no Nash Equilibrium is reached. To further continue analytical research, possible internal and external potential stability will be tested, which usually allows payment transfer. Potential internal stability means assuming given possibility of payment transfer, or called “optimal sharing rules”, i.e. whenever the coalition pay-off equals or exceeds the sum of the outside option pay-offs the coalition can be called potential internal stable. Potential external stability means the opposite that no player would be better off by joining the coalition if allowing payment transfer. Coalition is called a stable coalition if and only if it is internally and externally stable. For example, country A and B are in a small coalition and country C stays outside, which is potential stable. It means A or B would still be better off if they compensate the other party's gains of leaving the coalition to make it stay in. Country C maybe doesn't have an incentive to join this small coalition. Or the gains of country C by joining could be compensated by country A or B to make country C stay out. Even after the compensation, these countries will still all be better off (Weikard, 2009).

Game theory model is usually structuralized by different stages. For example, a relatively simple model could be characterized by two stages. In the first stage, countries decide if they join the international coalition or not and in the second stage, members of the coalition decide cooperatively about the amount of emissions abatement in a simultaneous play game and countries outside make their decision individually. A more complicated model could even have more stages, in this paper, three-stage model is set. Mathematically, an analytical model is also characterized by different exogenous parameters and endogenous variables. The setting depends on our research question. Finally, game theory model is usually solved by backward induction, which means the process of reasoning backwards in time, from the end of a problem or situation, to determine a sequence of optimal actions. It starts by first considering the last time a decision is made and then choosing what to do in the earlier stage considering this information. This process continues backwards until one has determined the best action for every possible situation (Kaminski, 2009).

4 Model Assumption:

4.1 Game Structure:

The structure of this game theory model is comprised of three stages, as shown in figure 1. In the first stage, countries decide about whether to choose climate policy cooperatively with the other countries or individually. Each country can set an energy tax on production to mitigate greenhouse gas emissions that cause damages from climate change in the second stage. Finally in the third stage of the game energy is traded on an international energy market.

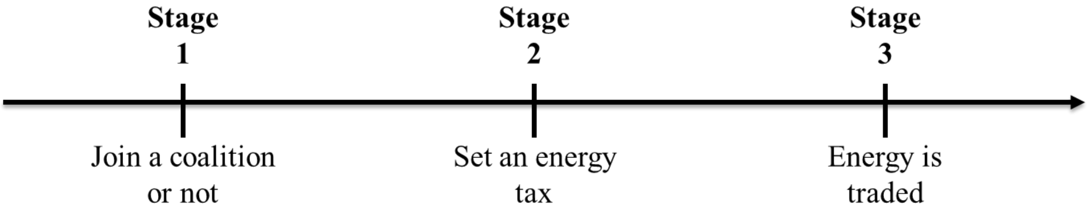

Figure 1 Structure of the game

4.2 Model Setting:

The main participants here are three countries, indexed by $i \in N$ with $N = \{1, 2, 3\}$. In each country, there are consumers and a representative producer producing energy from the amount q_i of its host country's specific fuel. Costs of energy production is shown as $C(q_i) = \frac{1}{2} c_i q_i^2$. Each country is endowed with a different fuel with different emission intensity e_i. Besides, the country is also harmed by the global environmental damage with a parameter δ_i. So the total emissions E are given by $E = \sum_i q_i e_i$. And environmental damage from emissions in each country is $D(E) = \delta_i E$. Finally energy tax on production is levied at τ_i^p.

The basic demand function and supply function of each country is set in the following way. The supply function is shown below.

$$q_i = \frac{p - \tau_i^p}{c_i} \tag{1}$$

It is derived from the first-order condition with regard to q_i of producer profit function

$$\pi_i = pq_i - \frac{1}{2}c_i q_i^2 - \tau_i^p q_i \tag{2}$$

Inverse demand function for energy in each country is identical.

$$p = a - by_i \tag{3}$$

Here a and b are both positive parameters and y_i represents the countries demand in energy. Market Clarence requires demand equals supply.

$$\sum_i y_i = \sum_i q_i \tag{4}$$

Here to simplify, welfare function of individual country is shown as below.

$$\begin{aligned}\max_{\tau_i^p} W_i(\tau_i^p) &= q_i^*(\tau_i^p)p^*(\tau_i^p) - \frac{1}{2}c_i\left(q_i^*(\tau_i^p)\right)^2 \\ &+ \frac{1}{2}\left(\frac{a - p^*(\tau_i^p)}{b}\right)\left(a - p^*(\tau_i^p)\right) - \delta_i \sum_i e_i q_i^*(\tau_i^p)\end{aligned} \tag{5}$$

Welfare is mainly made up of producer surplus, consumer surplus and environmental pollution damage. Consumer surplus needs to be mentioned here, as derived from market clarence quantity $\left(\frac{a - p^*(\tau_i^p)}{b}\right)$ and $\left(a - p^*(\tau_i^p)\right)$, as shown in figure 2. Tax is derived where first-order condition of welfare function is set to zero. Then optimal tax can be further calculated in each country with regard to different scenarios.

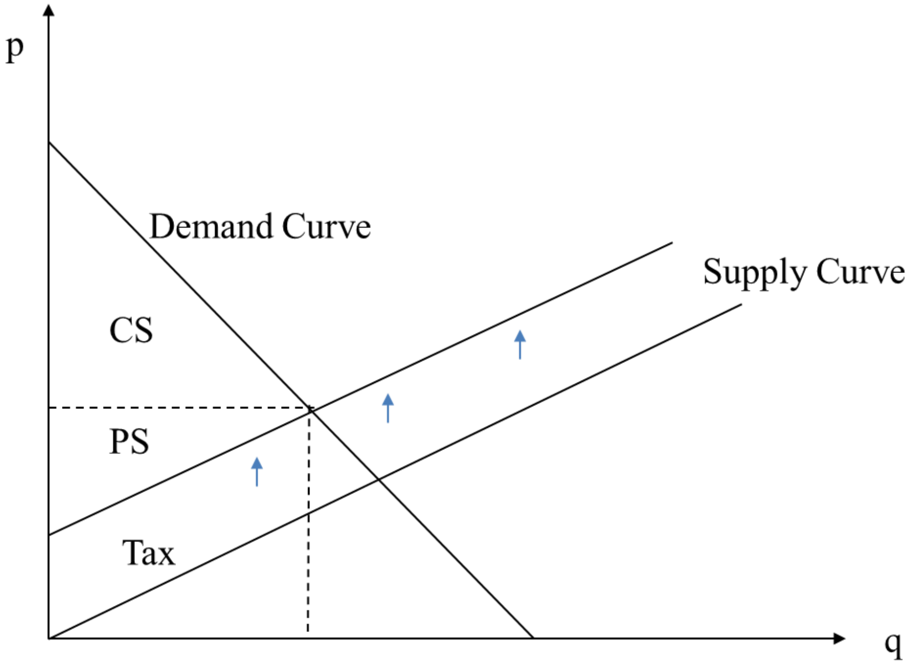

Figure 2 Welfare composition

This three-stage game theory model can be solved by backward induction. To summarize what has been discussed before, based on the model structure and setting, we will firstly solve the equation in the third stage by implementing market clarence condition. Market price and quantity for this equilibrium will be derived based on the first-order condition. Assuming other parameters unchanged, results will be interpreted between the producer tax and related quantity and price. In the following second stage, reaction functions will be derived based on different scenarios. Fives scenarios are: three countries form a grand coalition; no coalition is made at all; two countries form a coalition where the third country decides to be on itself. Symmetry is important here to simplify and interpret different dependency relationships between these three countries' tax policies. The tax implemented in one country is always related to the tax in the other two countries incorporated in reaction function. Besides, coalition structure, namely different scenarios all influence the form and level of reaction. Finally in the first stage, when the countries decide their participation in a coalition or not, the total welfare is what they focus. A country always pursues the participation to maximize its own welfare. Here numerical forms are applied to stimulate and interpret results. Also, possible potential stability needs to be tested where no Nash Equilibrium is found.

In this paper, some analytical results and conclusions are studied but still some limitations occur when finally proceeding to the first stage because of the increase in the complexity of the problem. Still, some interesting results can be interpreted in an analytical way to understand the behavior of three different countries in a simplified environmental coalition model considering inter-fossil fuel effect, which can be helpful to understand the more complicated cases of more countries' participation in an International Environmental Agreement.

5 Result:

5.1 The third stage:

Here firstly we started by implementing the third stage where energy is traded in the market using backward induction approach. Market Clarence is the condition to be satisfied here, which requires the sum of demand equals the sum of supply globally$\sum_i y_i = \sum_i q_i$. Market price and production quantity are calculated as below

$$p^*(\tau_i^p) = \frac{3a + b\sum_i \frac{\tau_i^p}{c_i}}{3 + b\sum_i \frac{1}{c_i}} \tag{6}$$

$$q_i^*(\tau_i^p) = \frac{3a + b\sum_i \frac{\tau_i^p}{c_i}}{c_i(3 + b\sum_i \frac{1}{c_i})} - \frac{\tau_i^p}{c_i} \tag{7}$$

Comparative static results can already be perceived here:

- An increase in the producer energy tax leads to a price increase in the energy market, as shown in $p^{*\prime}(\tau_i^p) > 0$; for example, when the tax is increased in a coal country, the market price will also follow the increase.

- An increase in producer tax in country i leads to a decrease of fuel production in this country, as shown in $q_i^{*\prime}(\tau_i^p) < 0$; for example, when the tax is increased in a coal country, the production quantity within this country will decrease.

- An increase in producer tax in country i leads to an increasing fuel production in other countries, as shown in $q_j^{*\prime}(\tau_i^p) > 0$, for example, in contrast with last point, a tax increase in coal country will cause a production quantity increase in other countries, such as oil or gas country.

5.2 The second stage:

In the second stage, countries set their energy tax to maximize their social benefit. Based on their decisions about whether to join a coalition or not in the first stage, different welfare functions exist which lead to different results. Here we choose three representative scenarios from the five ones mentioned before since three different cases where two countries join a coalition and third country stands alone are actually almost the same.

1. Grand coalition scenario:

We firstly implement the easiest scenario, where all these three countries form a grand coalition. In this case, it could be treated as a benchmark where global social welfare is maximized. It actually implies social optimum, whereas hard to implement in reality. The total social welfare function of these three countries is

$$W_0 = p^*(\tau_i^p)\sum_i q_i^*(\tau_i^p) - \frac{1}{2}\sum_i c_i\left(q_i^*(\tau_i^p)\right)^2 + 3 * \frac{1}{2}\left(\frac{a - p^*(\tau_i^p)}{b}\right)\left(a - p^*(\tau_i^p)\right) - \sum_i \delta_i \sum_i e_i q_i^*(\tau_i^p) \tag{8}$$

First-order condition with regard to the producer tax needs to be set to zero to maximize the gross welfare here and results are derived as below:

$$\tau_1^p = e_1(\delta_1 + \delta_2 + \delta_3)$$

$$\tau_2^p = e_2(\delta_1 + \delta_2 + \delta_3) \tag{9}$$

$$\tau_3^p = e_3(\delta_1 + \delta_2 + \delta_3)$$

It’s clear that the tax setting in each country is symmetric, positively related to the emission intensity and environmental damage, which means the larger emission intensity and higher environmental damage impact will lead to a higher producer tax. What needs to be noticed here, the difference of tax level lies between different countries is only related to their emission intensity, not their individual damage factor. Intuitively, it means that the whole damage is born together with all members together in the coalition, regardless of individual difference of damage impact and each country needs to be responsible with their own emission intensity. This grand coalition case is relatively easier to understand and its results fit intuitive perception. Generally, we can find big coalition creates pressure and has strong binding power to restrain its members' behavior regarding global carbon mitigation target.

It's more complicated when no grand coalition is formed. We will further elaborate the other four cases. Here we'll only discuss the case where country one and two form a coalition leaving country three alone as an example because of symmetry. But we will start with the other different case where no coalition exists and each country makes individual policy decision.

2. Individual country non-coalition scenario:

Non-coalition scenario here implies fully non-cooperative between three players. It will also be solved by backward induction approach, which is explained already in the methodology part. The welfare function for each individual country is set as below and the same first-order condition with regard to tax of each country is applied to derive the interaction function. Importantly, results from the third stage of equilibrium price and quantity function with regard to tax need to be substituted into this function before calculating on the derivative.

Objective function:

$$\begin{aligned} W_i(\tau_i^p) = {} & q_i^*(\tau_i^p)p^*(\tau_i^p) - \frac{1}{2}c_i\left(q_i^*(\tau_i^p)\right)^2 \\ & + \frac{1}{2}\left(\frac{a - p^*(\tau_i^p)}{b}\right)\left(a - p^*(\tau_i^p)\right) - \delta_i \sum_i e_i q_i^*(\tau_i^p) \end{aligned} \tag{10}$$

Reaction function of the first country is shown as below, since the other two countries' reaction function is symmetric with the first one, they are not presented here, details about the aggregated form of tax are elaborated in appendix 1.

$$\tau_1^p = (A_1 + B_1\delta_1 - D_{23}\tau_2^p - D_{32}\tau_3^p)/F_1 \tag{11}$$

Where

$$A_1 = -\frac{3abc_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} - \frac{3ac_1c_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} - \frac{ac_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$B_1 = \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)e_1}{c_1} - \frac{bc_2e_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} - \frac{bc_3e_2}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$D_{23} = \frac{b^2c_2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{bc_1c_2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$D_{32} = \frac{b^2c_3c_2^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{bc_1c_3c_2^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$F_1 = \frac{bc_2^2 c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{b^2c_2^2c_3^2}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{bc_2c_3}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}$$

Though the whole expression appears to be hard to read, our attention to analyze the reaction function can be guided by the following focus:

1. The first priority is always concentrating on the strategy variable that country 1 can use based on the strategies of the other two countries. In this case, the strategy variable is the producer tax. So we need to figure out the relationship between taxes of these countries.

2. Secondly, we will explore how other parameters, such as energy emission intensity and damage factor influence the tax instrument and finally cause impact for the final equilibrium.

3. The approach here used to accomplish the analysis target is mathematical derivation. When too hard to implement derivation, graph simulated by Mathematica software from a wide range of setting for certain parameters is also used to further investigate into the results.

Result 1. Consider the second stage of the game, where countries implement their producer tax,

1. In any case, as long as the positive condition is held by different parameters and variable such as a, b, $c_i, e_i,\ \delta_i, \tau_i^p$ to suit the model setting for reality, a positive relationship is proved between the tax in home country and other countries since

D_{23}, D_{32} are positive, while F_1 is proved to be negative.

2. Tax is also related to the environmental damage, with regard to a different relationship between all e_i parameters setting, when all parameters stay in a certain range:

    2.1 When e_i is almost the same within different countries, there exists a positive relationship between tax and environmental damage factor.

    2.2 When e_1 is significantly larger than emission intensity in the other two countries, there exists a positive relationship between tax and environmental damage factor.

    2.3 When e_1 is quite small and emission intensity in the other two countries is significantly larger than it, there exists a negative relationship between tax and environmental damage factor.

The explanation of result 1 is shown in appendix 2 by graph generated by Mathematica software. We'll have a further elaboration about the economic motivation behind this result. When each country makes its own economic decision instead of joining a coalition and making joint decision, still its own decision is influenced by other countries' decisions. If other countries decide to increase the tax, home country tends to increase it as well. It may sound against the economic intuitive perception of the common existence behavior, which shows the country usually intends to lower their effort, for example, lower their tax rate to enjoy the benefit from strict tax policies of other countries. But actually, it also makes sense if the country decides to do it the other way around instead of free-riding. Because in this model setting, the social welfare of each country consists of two parts, surplus from consumers and producer and damage from environmental pollution. Tax increase also has two effects here, lowering social surplus and lower the environmental damage. As long as the environmental damage reduction is higher compared with the loss of social surplus, home country does have the incentive to do so even knowing the other countries will increase their tax. However, it's even more complicated when the other countries make opposite decisions, which may also be influenced by their tax level but other parameters like cost that influenceD_{23}, D_{32}.

We’re also interested in how environmental damage factor of this country influences its tax level, however, different scenarios exist here depending on other factors, especially emission intensity level. So here we only choose three different scenarios to have a general idea about the economic logic. In 2.1 it means if all these countries have similar energy emission intensity, higher environmental damage rate will increase tax level in this country. 2.2 can be interpreted as when home country has very high emission intensity, far much higher than other countries, higher environmental damage rate will also increase tax level in this country. It’s different in 2.3 where home country has much lower energy emission intensity than other two countries, higher environmental damage rate will induce a lower tax. The explanation is also based on the theory of the double effect of tax introduced before. In the first two cases when home country pollutes much more than or similar than other countries, it still values the effect gains from reducing emission more than reduction of social surplus. So the higher damage it perceives from damage factor, the more tax it is willing to charge. However, when home country is the only country with the least emission intensity and the other countries emit too much, home country values more about their social surplus. Instead of increasing tax to reduce damage, which in this case is no longer economically viable, they shift to the other position to increase social welfare by lowering tax. It means because of the competitive advantage of the cheaper price of cleaner energy, home country gains more from international trade, which increases its social surplus and compensates the loss from pollution.

3. Country 1 and 2 form a coalition leaving country 3 alone

In this scenario, different welfare function is faced with countries inside a coalition and outside. Let’s take an example where country 1 and 2 join a coalition but country 3 steps out. Since country 3 has the same objective function and reaction function with the individual case, here the focus is targeted at the other two countries. Their objective function:

$$W_{12} = p^*(\tau_i^p)\sum\nolimits_{i=1,2} q_i^*(\tau_i^p) - \frac{1}{2}\sum\nolimits_{i=1,2} c_i\left(q_i^*(\tau_i^p)\right)^2 + 2 * \frac{1}{2}\left(\frac{a - p^*(\tau_i^p)}{b}\right)\left(a - p^*(\tau_i^p)\right) - \sum\nolimits_{i=1,2}\delta_i \sum_i e_i q_i^*(\tau_i^p) \qquad (12)$$

The calculation result for the reaction function is shown as below and details about the aggregated form of tax are elaborated in appendix 3.

$$\tau_1^p = (\widetilde{A_1} + \widetilde{B_1}(\delta_1 + \delta_2) - \widetilde{D_{23}}\tau_2^p - \widetilde{D_{32}}\tau_3^p)/\widetilde{F_1} \qquad (13)$$

Where

$$\widetilde{A_1}$$

$$= -\frac{3abc_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} - \frac{6ac_1c_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$- \frac{2ac_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$- \frac{3ac_2c_3\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$+ \frac{3ac_1c_2c_3\Bigg(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$\widetilde{B_1} = \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)e_1}{c_1} - \frac{bc_2e_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} - \frac{bc_3e_2}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$\widetilde{D_{23}}$$

$$= \frac{b^2c_2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{2bc_1c_2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$
$$+ \frac{bc_3\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$
$$- \frac{bc_1c_3\left(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$\widetilde{D_{32}}$$

$$= \frac{b^2c_3c_2^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_3c_3)^2} + \frac{2bc_1c_3c_2^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$
$$+ \frac{bc_2\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$
$$- \frac{bc_1c_2\left(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$\widetilde{F_1}$$

$$= \frac{2bc_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{b^2c_2^2c_3^2}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$
$$+ \frac{bc_2c_3}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)}$$
$$+ \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}$$
$$+ \frac{bc_2c_3\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)}$$
$$- \frac{bc_3c_2\left(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

Result 2. Consider the second stage of the game, where countries implement their producer tax,

1. In any case, as long as the positive condition is held by different parameters and variable such as a, b, $c_i, e_i,\ \delta_i, \tau_i^p$ to suit the model setting for reality, a positive relationship is proved between the tax in home country and other countries since $\widetilde{D_{23}}, \widetilde{D_{32}}$ are positive , while $\widetilde{F_1}$ is proved to be negative. Besides, the other country stays in the same coalition has a smaller impact level while the country out of the coalition has a larger impact compared with themselves in non-coalition case.

2. Tax is also related to the environmental damage, with regard to a different relationship between all e_i parameters setting, when all parameters stay in a certain range:

   2.1 When e_i is almost the same within different countries, there exists a positive relationship between tax and the sum of environmental damage factor of two countries within a coalition.

   2.2 When e_1 is significantly larger than emission intensity in the other two countries, there exists a positive relationship between tax and the sum of environmental damage factor of two countries within a coalition.

   2.3 When e_1 is quite small and emission intensity in the other two countries is significantly larger than it, there exists a negative relationship between tax and the sum of environmental damage factor of two countries within a coalition.

The explanation of result 2 is shown in appendix 4 by graph generated by Mathematica software. This result is almost the same as the non-coalition case. In the first part, joining a coalition wouldn't alter the country's preference in their decision when facing other player's policy. In this model setting, they will increase when other countries decide to increase the tax, vice versa. The logic is explained before as in result 1. The curiosity is the different level of impacts compared with the former non-coalition case. Further discussion is based on the tested result that $\frac{\widetilde{D_{23}}}{\widetilde{F_1}} - \frac{D_{23}}{F_1} > 0, \frac{\widetilde{D_{32}}}{\widetilde{F_1}} - \frac{D_{32}}{F_1} < 0$ will always hold regardless of the scale for the parameters of cost or b, as long as they satisfy the basic positive setting. It can be interpreted that the level of impact of the other country within this coalition, in this case country 2 is smaller while the country out of the coalition is bigger compared with non-coalition case, which means joining a coalition mitigates the level of impact of the other countries within a coalition but amplify the impact of other countries out of this coalition from tax level. In the second part, since $\widetilde{B_1} = B_1$ the interpretation of emission damage factor with regard to different range of emission intensity is the same. But attention needs to be drawn on that the tax is finally decided by the sum of the coalition countries' damage factor, which indicates the possibility of offset effect. For example, one country has a high damage sensitivity, but the other country is feeling less from the damage, finally, their aggregated impact is probably only intermediate.

Besides, the third country out of a coalition has the same reaction behavior with non-coalition case. Since the tax is not finally calculated here in parametric form, from this point till the first stage, numerical models will be mostly used.

5.3 The first stage:

In this first stage where countries make their decision to join a coalition or stay alone, we're motivated to understand the mechanism and how different incentive influence the tax policy and rent distribution.

5.3.1 Symmetric countries

To start with the simplest case where all these countries are identical to each other, we can have a basic idea about how welfare varies in different cases with regard to different taxes.

1. Individual country:

Tax for each country:

$$\tau_p = \frac{3ce\delta}{2b+3c} \tag{14}$$

Welfare for each country:

$$\mathrm{W} = \frac{(2ab+3ac-3ce\delta)\big(a(2b+3c)\big)-3(4b+5c)e\delta)}{2(b+c)(2b+3c)^2} \tag{15}$$

2. Small coalition between two countries, since these countries are symmetric, the result would be the same if we switch countries. So three different small country coalition cases are simplified into just one, for example, country 1 and country 2 from a coalition, but country 3 stands alone:

Tax for each country:

$$\tau_{p1} = \tau_{p2} = \frac{2(10bce\delta+9c^2e\delta)}{(b+c)(4b+9c)} \tag{16}$$

$$\tau_{p3} = \frac{2(7bce\delta+9c^2e\delta)}{(b+c)(4b+9c)} \tag{17}$$

Welfare for each country:

$$W_1 = W_2 = \frac{a^2(b+c)-6a(b+c)e\delta+\frac{4c(89b^2+252bc+162c^2)e^2\delta^2}{(4b+9c)^2}}{2(b+c)^2} \tag{18}$$

$$W_3 = \frac{a^2(b+c)-6a(b+c)e\delta+\frac{8c(70b^2+153bc+81c^2)e^2\delta^2}{(4b+9c)^2}}{2(b+c)^2} \tag{19}$$

3. Grand coalition:

Tax for each country:

$$\tau_p = 3e\delta \qquad (20)$$

Welfare for each country:

$$\mathrm{W} = \frac{(a - 3e\delta)^2}{2(b + c)} \qquad (21)$$

Proposition 1. Coalition pattern has an impact on the tax level within each symmetric country. The tax level can be ordered as below (proof is shown in appendix 5):

$$\tau_{\text{individual country}}(14) < \tau_{\text{country within small coalition}}(17)$$
$$< \tau_{\text{country outside small coalition}}(16) < \tau_{\text{grand coalition}}(20)$$

Besides, the welfare comparison between these three different scenarios is shown as below.

$$W_{\text{individual country}}(15) < W_{\text{country within small coalition}}(18)$$
$$< W_{\text{country outside small coalition}}(19) < W_{\text{grand coalition}}(21)$$

Based on simulated graph in Appendix 6, it shows within certain parameter range, the above relationship of welfare will always hold.

To find out the Nash equilibrium, we decide to use decision matrix. The idea of decision is to assume one country is aware of the other participants' decision possibility and then choose the best decision to maximize its own welfare.

Firstly, we try to find the matrix for country 1. So we find out there are only four possible scenarios where country 2 and country 3 make their decisions about participation in a coalition or not. There are only four possibly scenarios, as shown in the first and second column in table 1. Second, country 1 makes its own decision. The rule for country 1 to make a rational decision to join or not is to compare its own welfare regarding his different decision, which can be also called strategy space in game theory model. For example, assuming country 2 and country 3 choose to stay in a coalition, as shown in the first row in table 1, if country 1 decides to join, its own welfare equals equation (21). If country 1 decides to not join, its own welfare equals equation (19). To mention here, the coalition pattern changes regarding the different decisions made, which influences the final welfare. Since (21) is proved to be larger than (19), country 1 will choose to stay in a coalition. We can use the same logic to calculate the whole decision matrix for country 1, as shown in table 1.

Table 1 Decision matrix for country 1

Assumption for country 2	**Assumption for country 3**	**Decision of country 1**
In a coalition	In a coalition	In a coalition
In a coalition	Not in a coalition	In a coalition
Not in a coalition	In a coalition	In a coalition
Not in a coalition	Not in a coalition	Not in a coalition

Since all countries are symmetric in model setting, different coalition pattern is the main factor that influences the welfare. And welfare comparison are discussed before. Since the decision of country 1 is also the same decision of country 2 and country 3, Nash Equilibrium exists where each country makes the same decision. So technically here exist two Nash Equilibrium where non-coalition is formed and the grand coalition is formed. Before further elaboration, we need to clarify here since obviously the welfare in grand coalition for each country is absolutely higher than that in non-coalition case, how come non-coalition case can still be a Nash Equilibrium? Because the model setting is relatively special. In this three-country game, as long as two other countries decide to not join a coalition, the third country can’t choose other decision but to quit coalition since the country itself alone can’t form any coalition. So this special Nash Equilibrium exists only because of our model setting. Later in the asymmetric country case, it will recur.

So in symmetric country case, the grand coalition is a stable Nash Equilibrium where every country gains the highest welfare without incentive to leave. According to the comparison, from non-coalition to small coalition and then to the grand coalition scenario, the higher the coalition level is reached, the higher tax level is and the higher the welfare is. Though it seems counterintuitive, it makes sense when considering environmental damage into the whole welfare function during the policy decision stage. In symmetric countries setting, according to the objective function of welfare, the welfare from environmental damage is only related to the quantity of global fossil fuel, since emission intensity and environmental damage parameter for each country is identical. The quantity of fossil fuel in the individual country scenario is highest, followed by the small coalition scenario and the grand coalition scenario. So the negative loss of welfare from grand coalition case is the least among all scenarios, which means in the grand coalition where the highest tax is implemented, each country compensates the fossil fuel trade loss greatly from reducing environmental damage. The grand coalition achieves social optimum from a social planner perspective. Mathematical explanation is presented in appendix 6.

5.3.2 Asymmetric countries

Asymmetric countries are more commonly existing globally. In our model setting, we assume country 1 as the main coal country that specializes in coal production, while country 2 as the oil country and country 3 as the gas country, which are also perceived as relatively cleaner countries. In this first stage, to gain further insights into countries' strategic decision and motivation, we decide to use numeric models. Considering model setting background for these three typical fossil fuel countries, cost, emission intensity and environmental damage parameters are assumed as below in (22). Cost and emission intensity of different fossil fuels are derived from several reports (Bauer, Mouratiadou, & Luderer, 2013; *BP Statistical Review of World Energy*, 2018; International Energy Agency, 2016). Environmental impact parameter here is assumed to be identical between different countries and "a" from inverse demand function is set to be 100 for simplicity.

$$c_1 = 6.12 \; c_2 = 29.16 \; c_3 = 15.48 \tag{22}$$

$$e_1 = 0.3852 \; e_2 = 0.26388 \; e_3 = 0.20196$$

$$\delta_1 = 15 \; \delta_2 = 15 \; \delta_3 = 15$$

$$a = 100$$

Under these parameter setting for our simplified model, the only parameter left here is price elasticity of demand 1/b. We are interested in analyzing how different coalitions and non-coalition are implemented strategically by these three countries in the first stage by assuming different elasticities. The range of price elasticity of demand 1/b will be between 0.74 and 3.0. Many linear regression models were implemented to estimate demand elasticity of fossil fuel from early researches. 0.74 represents the average level of several results. However, considered as a relatively rough estimation, we may still need to use it since it fits our simply model assumption of a linear demand (Dahl, 2006). Besides, 3.0 is the maximum elasticity of crops in several linear estimation models, which is considered here as a reference of upper threshold since usually the demand elasticity of fossil fuel is generally considered to be no higher than crops(Hee, 1967).

Simulation results are shown from table 2 to table 5, where price elasticity of demand 1/b=0.74, 1.25, 1.5, 3. Further results where price elasticity of demand 1/b=1, 1.75 are also included in appendix 7.

Table 2 Simulation Result of Elasticity = 0.74

	S1: Individual Country	S2: Grand Coalition	S3: 1,2 Small Coalition	S4: 1,3 Small Coalition	S5: 2,3 Small Coalition
Tax country 1	8.22	17.33	12.00	13.20	8.25
Tax country 2	1.72	11.87	8.36	1.87	4.58
Tax country 3	1.89	9.09	2.00	7.70	2.72
Price	90.05	90.98	90.39	90.53	90.11
Supply Quantity country 1	13.37	12.03	12.81	12.64	13.38
Supply Quantity country 2	3.03	2.71	2.81	3.04	2.93
Supply Quantity country3	5.69	5.29	5.71	5.35	5.65
Welfare 1	587.10	585.48	587.48	587.27	588.02
Welfare 1-pollution	-106.49	-96.29	-102.44	-101.25	-106.00
Welfare 1-social surplus	693.59	681.77	689.93	688.52	694.02
Welfare 1-social surplus-producer	656.94	651.63	655.76	655.33	657.83
Welfare 1-social surplus-consumer	36.65	30.14	34.16	33.19	36.19
Welfare 2	69.14	73.35	70.62	72.40	69.06
Welfare 2-pollution	-106.49	-96.29	-102.44	-101.25	-106.00
Welfare 2-social surplus	175.63	169.63	173.06	173.66	175.06
Welfare 2-social surplus-producer	138.99	139.50	138.90	140.46	138.87
Welfare 2-social surplus-consumer	36.65	30.14	34.16	33.19	36.19
Welfare 3	191.95	198.51	195.50	194.73	192.22
Welfare 3-pollution	-106.49	-96.29	-102.44	-101.25	-106.00
Welfare 3-social surplus	298.44	294.80	297.94	295.99	298.22
Welfare 3-social surplus-producer	261.79	264.66	263.78	262.79	262.03
Welfare 3-social surplus-consumer	36.65	30.14	34.16	33.19	36.19
Global emission	7.10	6.42	6.83	6.75	7.07

Table 3 Simulation Result of Elasticity = 1.25

	S1: Individual Country	**S2: Grand Coalition**	**S3: 1,2 Small Coalition**	**S4: 1,3 Small Coalition**	**S5: 2,3 Small Coalition**
Tax country 1	7.36	17.33	11.85	12.60	7.38
Tax country 2	2.52	11.87	8.21	2.61	5.78
Tax country 3	2.30	9.09	2.37	7.10	3.92
Price	93.82	94.42	94.05	94.11	93.88
Supply Quantity country 1	14.13	12.60	13.43	13.32	14.13
Supply Quantity country 2	3.13	2.83	2.94	3.14	3.02
Supply Quantity country3	5.91	5.51	5.92	5.62	5.81
Welfare 1	626.65	622.57	626.14	625.91	627.76
Welfare 1-pollution	-111.94	-100.68	-107.20	-106.41	-111.23
Welfare 1-social surplus	738.59	723.24	733.35	732.32	738.99
Welfare 1-social surplus-producer	714.73	703.76	711.25	710.66	715.54
Welfare 1-social surplus-consumer	23.86	19.48	22.10	21.66	23.44
Welfare 2	62.75	69.24	65.42	67.01	62.75
Welfare 2-pollution	-111.94	-100.68	-107.20	-106.41	-111.23
Welfare 2-social surplus	174.69	169.92	172.63	173.42	173.98
Welfare 2-social surplus-producer	150.82	150.44	150.53	151.76	150.54
Welfare 2-social surplus-consumer	23.86	19.48	22.10	21.66	23.44
Welfare 3	196.07	204.07	200.44	199.71	196.36
Welfare 3-pollution	-111.94	-100.68	-107.20	-106.41	-111.23
Welfare 3-social surplus	308.01	304.75	307.64	306.12	307.59
Welfare 3-social surplus-producer	284.14	285.27	285.54	284.46	284.15
Welfare 3-social surplus-consumer	23.86	19.48	22.10	21.66	23.44
Global emission	7.46	6.71	7.15	7.09	7.42

Table 4 Simulation Result of Elasticity = 1.5

	S1: Individual Country	S2: Grand Coalition	S3: 1,2 Small Coalition	S4: 1,3 Small Coalition	S5: 2,3 Small Coalition
Tax country 1	7.12	17.33	11.81	12.44	7.14
Tax country 2	2.73	11.87	8.17	2.81	6.10
Tax country 3	2.41	9.09	2.47	6.94	4.24
Price	94.79	95.30	94.99	95.03	94.84
Supply Quantity country 1	14.32	12.74	13.59	13.50	14.33
Supply Quantity country 2	3.16	2.86	2.98	3.16	3.04
Supply Quantity country3	5.97	5.57	5.98	5.69	5.85
Welfare 1	636.94	632.19	636.19	635.98	638.08
Welfare 1-pollution	-113.34	-101.80	-108.42	-107.73	-112.57
Welfare 1-social surplus	750.29	733.99	744.61	743.71	750.65
Welfare 1-social surplus-producer	729.92	717.39	725.79	725.21	730.67
Welfare 1-social surplus-consumer	20.37	16.60	18.83	18.50	19.98
Welfare 2	60.96	68.09	63.97	65.49	60.99
Welfare 2-pollution	-113.34	-101.80	-108.42	-107.73	-112.57
Welfare 2-social surplus	174.30	169.89	172.40	173.22	173.57
Welfare 2-social surplus-producer	153.94	153.30	153.57	154.72	153.59
Welfare 2-social surplus-consumer	20.37	16.60	18.83	18.50	19.98
Welfare 3	197.05	205.45	201.65	200.92	197.34
Welfare 3-pollution	-113.34	-101.80	-108.42	-107.73	-112.57
Welfare 3-social surplus	310.39	307.25	310.07	308.65	309.91
Welfare 3-social surplus-producer	290.02	290.66	291.25	290.15	289.94
Welfare 3-social surplus-consumer	20.37	16.60	18.83	18.50	19.98
Global emission	7.56	6.79	7.23	7.18	7.50

Table 5 Simulation Result of Elasticity = 3

	S1: Individual Country	S2: Grand Coalition	S3: 1,2 Small Coalition	S4: 1,3 Small Coalition	S5: 2,3 Small Coalition
Tax country 1	6.49	17.33	11.69	12.02	6.50
Tax country 2	3.31	11.87	8.05	3.35	6.96
Tax country 3	2.70	9.09	2.74	6.52	5.10
Price	97.31	97.58	97.42	97.44	97.34
Supply Quantity country 1	14.84	13.11	14.01	13.96	14.84
Supply Quantity country 2	3.22	2.94	3.06	3.23	3.10
Supply Quantity country3	6.11	5.72	6.12	5.87	5.96
Welfare 1	664.05	657.46	662.62	662.50	665.21
Welfare 1-pollution	-117.03	-104.71	-111.60	-111.21	-116.09
Welfare 1-social surplus	781.08	762.18	774.23	773.71	781.30
Welfare 1-social surplus-producer	770.25	753.40	764.27	763.87	770.72
Welfare 1-social surplus-consumer	10.82	8.78	9.96	9.84	10.58
Welfare 2	55.99	64.92	59.99	61.24	56.14
Welfare 2-pollution	-117.03	-104.71	-111.60	-111.21	-116.09
Welfare 2-social surplus	173.02	169.63	171.59	172.45	172.23
Welfare 2-social surplus-producer	162.19	160.86	161.63	162.60	161.65
Welfare 2-social surplus-consumer	10.82	8.78	9.96	9.85	10.58
Welfare 3	199.44	208.95	204.68	203.92	199.72
Welfare 3-pollution	-117.03	-104.71	-111.60	-111.21	-116.09
Welfare 3-social surplus	316.47	313.67	316.28	315.13	315.81
Welfare 3-social surplus-producer	305.64	304.89	306.32	305.29	305.23
Welfare 3-social surplus-consumer	10.82	8.77	9.96	9.85	10.58
Global emission	7.80	6.98	7.44	7.41	7.74

To be clear, the results discussed below are all based on these numerical models. And it only supports to analyze the mechanism and even rent distribution behind environment coalition under certain parameters, or certain ranges. When condition falls out of these numerical models, results possibly may not hold any more. Some results are summarized as below.

Result 3. Within each elasticity simulation scenario, there always exists a dominant strategy for the gas country to choose to stay in a coalition. When elasticity is 1.25 or higher, there may also exist a dominant strategy for coal country to always choose to stay out of a coalition. However, the dominant strategy for oil country may only exist when the elasticity is relatively higher, between 1.5 and 3. Under a certain elasticity value or range, there exists a small coalition between oil and gas countries as Nash Equilibrium besides individual country Nash Equilibrium (as we mentioned before, it results from model setting and we will not focus on it here), e.g. when the elasticity of demand is relatively higher between 1.5 and 3.

A strategy is dominant, if it gives a player a higher payoff than any other strategy, regardless of the strategy chosen by other players. If one strategy is dominant, all other strategies are dominated (Fudenberg, D. & Tirole, J. 1991). To check if dominant strategy exists, a decision matrix for each country is made as below. For example in Table 2 where elasticity = 0.74 and Table 5 where elasticity = 3, considering possible choices of the other two countries, the decision of the third country could be made by comparing its own welfare regarding their choice to join a coalition or not, which is shown as below in table 6 and table 7.

In decision matrix, we assume the other two countries firstly make their possible decisions and then check what the best decision the third country can make to maximize its own welfare. In table 6, the first two columns present the assumption where two countries make their decisions already. In the third column, the possible welfare of the third country is listed based on its decision. It will always choose its decision that brings the highest welfare. The shadow color demonstrates the duplicate scenario appears in the decision matrix of each country which is a Nash Equilibrium.

Table 6 Decision matric where elasticity = 0.74

Assumption for country 2	**Assumption for country 3**	**Decision of country 1: welfare**
In a coalition	In a coalition	In a coalition: 585.48 **Not in a coalition: 588.02**
In a coalition	Not in a coalition	**In a coalition: 587.48** Not in a coalition: 587.10
Not in a coalition	In a coalition	**In a coalition: 587.27** Not in a coalition: 587.10
Not in a coalition	Not in a coalition	**In a coalition: 587.10** **Not in a coalition: 587.10**

Assumption for country 1	**Assumption for country 2**	**Decision of country 3: welfare**
In a coalition	In a coalition	**In a coalition: 198.51** Not in a coalition: 195.50
In a coalition	Not in a coalition	**In a coalition: 194.73** Not in a coalition: 191.95
Not in a coalition	In a coalition	**In a coalition: 192.22** Not in a coalition: 191.95
Not in a coalition	Not in a coalition	**In a coalition: 191.95** **Not in a coalition: 191.95**

Assumption for country 1	**Assumption for country 3**	**Decision of country 2: welfare**
In a coalition	In a coalition	**In a coalition: 73.35** Not in a coalition: 72.40
In a coalition	Not in a coalition	**In a coalition: 70.62** Not in a coalition: 69.14
Not in a coalition	In a coalition	In a coalition: 69.06 **Not in a coalition: 69.14**
Not in a coalition	Not in a coalition	**In a coalition: 69.14** **Not in a coalition: 69.14**

Table 7 Decision matric where elasticity = 3

Assumption for country 2	Assumption for country 3	Decision of country 1: welfare
In a coalition	In a coalition	In a coalition: 657.46 **Not in a coalition: 665.21**
In a coalition	Not in a coalition	In a coalition: 662.62 **Not in a coalition: 664.05**
Not in a coalition	In a coalition	In a coalition: 662.50 **Not in a coalition: 664.05**
Not in a coalition	Not in a coalition	**In a coalition: 664.05** **Not in a coalition: 664.05**

Assumption for country 1	Assumption for country 2	Decision of country 3: welfare
In a coalition	In a coalition	**In a coalition: 208.95** Not in a coalition: 204.68
In a coalition	Not in a coalition	**In a coalition: 203.92** Not in a coalition: 199.44
Not in a coalition	In a coalition	**In a coalition: 199.72** Not in a coalition: 199.44
Not in a coalition	Not in a coalition	**In a coalition: 199.44** **Not in a coalition: 199.44**

Assumption for country 1	Assumption for country 3	Decision of country 2: welfare
In a coalition	In a coalition	**In a coalition: 64.92** Not in a coalition: 61.24
In a coalition	Not in a coalition	**In a coalition: 59.99** Not in a coalition: 55.99
Not in a coalition	In a coalition	**In a coalition: 56.14** Not in a coalition: 55.99
Not in a coalition	Not in a coalition	**In a coalition: 55.99** **Not in a coalition: 55.99**

Country 3, the clean gas country will always choose to join a coalition regardless of other countries' choice between these two scenarios. While, in the case where price elasticity of demand equals 3, both country 1 and country 2 also have their dominant strategies regardless of other countries' decisions. It means here the coal country's dominant strategy is to leave a coalition while oil country will always choose to stay in a coalition.

Nash Equilibrium exists when each country uses their dominant strategy. In the case where the dominant strategy is not clear for each country, the duplication between these three countries' decision matrixes could be considered as a Nash Equilibrium. As we discussed before, non-coalition will always be a Nash Equilibrium because of model setting. So in the simulation results, when elasticity increased from 0.74 to 1.25, still there is only one possible non-coalition Nash Equilibrium. But when it reaches 1.5 and increases till 3, another possible small coalition between two clean countries comes to existence.

As our model already shows the possibility of the grand coalition in symmetric country case, this possibility of a small coalition in asymmetric country implies to resolve climate change problem in real life by international coalition could work. Different fossil fuel countries could all benefit when considering environmental damage into their welfare targets.

The mechanism behind the decision making part for countries in the first stage is rooted in welfare comparison, which means the country will always choose the strategy that brings them higher welfare. Welfare is composed of two parts, welfare from environmental pollution loss and welfare from economic social surplus. The latter includes social surplus from both consumers and producers. The shift from non-coalition Nash Equilibrium to clean country small coalition Nash Equilibrium is driven by welfare increase of countries. As we know coalition has strong constraint force in its members to lower environmental damage by increasing their tax level, which will increase the environmental welfare for all countries. A higher tax usually harms social surplus welfare from consumers and producers side. Compared with non-coalition scenario, the small coalition between clean countries increase each countries environmental welfare significantly, which could compensate their social surplus welfare loss. To be more specifically about each country's situation if shifted from non-coalition scenario to grand coalition scenario, according to the numerical models where elasticity ranges from 0.74 to 3, coal country and gas country have welfares gains, for sure comes from improvement of environmental damage, sometimes even increase from producer surplus, but always loss for consumer surplus; oil country doesn't always have welfares gains, for sure always gains comes from improvement of environmental damage, but sometimes can't be compensated by the increase of environmental damage welfare. A possible explanation here also returns to our model setting. Considering oil country usually has a higher cost ($c_2 = 29.16$), its comparative advantage is relatively lower than other countries. And social surplus loss is even harder to compensate.

Result 4. Within each elasticity simulation scenario, the grand coalition is always potentially internal and external stable if transfer payment is allowed. It means the case where small coalition Nash Equilibrium exists could be possibly shifted to a grand coalition if we can loosen the constraint by allowing negotiation of transfers between these countries. In the case where only non-coalition exists, it's also possible to reach a potentially stable grand coalition by allowing transfer payments.

Let's start first with the case where we could reach a small coalition NE, e.g. price elasticity of demand equals 3. To shift from small coalition to grand coalition, only coal country will suffer from welfare loss of 7.75 (equal to 657.46-665.21, table 5). In contrast, both oil and gas country will gain more welfares at around 9. Cleaner countries will have a strong motivation to make sure this shift to grand coalition happens by compensating coal country because they still can have extra gains after compensation. Though it seems possible from the motivation perspective, we still need to check the potential internal stability, which means if one of these countries has the incentive to leave the coalition given the payment. Coal country has no incentive to leave. Assuming it receives the transfer from both two countries so that its welfare is already larger than what he could receive by staying in small coalition. As we can see, small coalition welfare 665.21 (table 5) already represents the highest welfare coal country could achieve compared with the other four scenarios. So the coal country will not leave if receive this payment. However, for oil and gas countries, they may have the incentive to leave if they receive less welfare compared with the scenario where it stands alone out of a small coalition between the other two countries. For example, if what oil country could get is less than 61.24, which represents its welfare in the scenario where gas and coal country make a small coalition, after compensating coal country's loss, this internal stability would be broken. So the compensation from oil country and gas country has a limitation. They can't afford it anymore once beyond. The limitation is the welfare difference between grand coalition and the small coalition where corresponding country stands outside. So limitation for oil country is 3.68 (equal to 64.92-61.24, table 5), for gas country is 4.27 (equal to 208.95-204.68, table 5). The sum of their affordable compensation is 7.95, which exceeds what coal country needs to stay in (7.75). So the grand coalition is potentially internal and external stable. It works in the same way when elasticity decreases to 1.5.

Then in the case only non-coalition Nash Equilibrium exists, we need to check the potential stability of the grand coalition in two steps. Firstly, we need to check if non-coalition case can be shifted to a potential stable small coalition. Second, we need to check if the small coalition case can be shifted to a potential stable grand coalition. The reason is from the definition of Nash Equilibrium, only one player can change his decision assuming others stay the same every time. So the case where every player decides to change their decision together can't be considered. Let's start with the first step. For example, to check the potential internal stability of small coalition between coal and oil countries, the total welfare of both countries staying inside the coalition should be larger than their total welfare when they stay outside (587.48+70.62>587.10+69.14, table 2). We can use the same way to test the internal stability for the other two small coalitions. It turns out all small coalitions are potentially internal stable. Then we need to test the external stability of the small coalition to see if the third country has an incentive to step in. We continue with the coal and oil coalition case. The total welfare of grand coalition case is always higher than any small coalition since it reaches social optimum by reaching grand coalition. So the potential external stability no longer holds for small coalition case. Finally let’s check the potential internal stability of grand coalition case. Since there are only three countries, so there is no need to check external stability. A grand coalition with potential internal stability is actually a potential stable coalition. We need to check if the total welfare of grand coalition (585.48+73.35+198.51, table 2) is larger than the total welfare of three countries when each of them leaves a grand coalition assuming other countries remain inside (588.02+72.40+195.50, table 2) (Weikard, 2009) . So in this case, the grand coalition is potential stable.

Based on our simulation results, it’s clear that the global welfare reaches the highest level in grand coalition case. It can be imagined that a benevolent dictatorship above the governments of three countries makes decisions with regard to the benefit of the population as a whole, which means to maximize the global welfare in this case. The highest welfare in the grand coalition could be a possibly necessary condition for its potential stability. To summarize what we already discussed before, the real welfare of coal country is slightly above the highest welfare it could achieve within these five possible coalition scenarios after transfer payment. Coal country received the highest welfare when two cleaner countries form a small coalition and it stands alone. The other two clean countries receive slightly above the second-highest welfare it could achieve within these five possible coalition scenarios after transfer payment. For them the highest welfare are achieved in the grand coalition case. The second-highest exist when the other two countries form a small coalition and it stands alone. Since all three countries receive at least above second-highest welfare in the final stage after a transfer, the total welfare in the grand coalition has to be high enough to support it to happen.

6 Discussion:

Does it always exist a dominant strategy for different countries? Based on our model, there always exists a dominant strategy of joining a global coalition for the gas country.

When the elasticity increases even higher, coal country may have a dominant strategy of not participating in a coalition while oil country has a dominant strategy of participating in a coalition. A dominant strategy may appear to be quite common within our model setting, since here the welfare of each country is only decided by their economic social surplus and environmental pollution welfare. However, in reality besides the welfare mentioned before, the decisions also depend on many more complicated issues, such as available information, political power and so on. United States' withdrawal from the Paris Agreement shows there can be various factors that finally decides a country's climate strategy. A dominant strategy maybe only exists in a relatively ideal environment.

Further results from the numerical model of the first stage show a promising future with lower carbon emission by demonstrating the possibility of forming a strong climate coalition of cleaner countries or even a bigger global coalition by allowing transfer payment from cleaner countries to coal country. The milestones of global climate negotiations already proved that necessary financial support, e.g. transfer payment is in need. For example, in Conferences of the Parties 15, there is an emphasis on financial support. In the long term, "developed countries commit to a goal of mobilizing jointly 100 billion dollars a year by 2020 to address the needs of developing countries" (UNFCCC, 2010). Here developed countries mainly refer to countries that rely on oil and gas consumption while most developing countries are coal consuming countries. So the compensation from cleaner countries to coal countries is justified to establish a stable climate coalition with lower emission.

In our numerical model, what's proved next after transfer payment is the welfare distribution pattern that the coal country's welfare will be above its first best welfare among all possible coalition scenarios while other cleaner countries' welfare will be only above their second-best welfare. In our game theory model, it's proved to be possible since it's based on a voluntary decision driven by welfare increase. It means though it seems a bit hard for gas and oil country to sacrifice their welfare to compensate coal country with significant welfare increase, these two cleaner countries will still prefer to do so because their welfares are also better off. Two cleaner countries will end up with even less than second-best welfares if they decide to not to compensate coal country. This result further justifies the necessity of compensation to achieve a global coalition. Cleaner countries, especially rich developed countries should be ready to pay for this price when considering possible loss and gains at the same time. In our model, it’s proved the gain could be possibly larger than loss and it’s logical to compensate.

7 Conclusion:

Supply side policy, such as producer tax in the climate coalition has demonstrated significant potential in recent research. A necessary focus especially needs to be attached to the position of different countries based on different inter-fossil fuel effects and environmental damage consciousness. In this paper, some conclusions can be summarized by studying the interaction between different fossil fuel producers and country governments

In the second stage of deciding producer tax within each country, when a grand coalition of all countries are formed, their final tax in each country is only influenced by its own carbon emission intensity and the sum of their sensitivity to environmental damage. While in other cases where no grand coalition is formed, one country, no matter inside or outside a small coalition, their tax is always positively related to other countries' tax. The level of the other countries' impact can be different, the country within the same coalition usually influences less while the country outside more from the tax level. So the coalition here means a stronger binding power. Besides, regarding different emission setting of each country, the final impact of damage factor on tax could also be different, positively or even negatively. In the small coalition case, the only big difference is the sum of damage factors of coalition countries is taken into account, the conclusion holds the same with the same emission factor range.

In the first stage of making coalition decision, when assuming symmetric country condition, a grand coalition NE could exist where the tax level is highest but also each country receives the highest welfare, which reaches social optimum. If we assuming asymmetric country case, as shown in our numerical models, when price elasticity of demand is relatively high, besides non-coalition NE, there could possibly exist another NE where cleaner countries: gas country and oil country form a small coalition, which could actually lower the global emission level compared with the other NE. Further, if transfer payments is allowed between different countries through negotiation, a possible potential internal and external stable grand coalition could be achieved, even if we loosen the elasticity condition. In this case, the global emission level could be reduced to the least.

This paper proves the reasonability and incentive behind a simplified IEA considering inter-fossil fuel effects. What’s more promising here is mentioned as a grand potential stable coalition to achieve the highest global environmental welfare. However, in real life, though transfer payment could be issued, the negotiation process to address it may even cause more extra cost which may finally break the equilibrium. As in COP meets every year, though some results have been reached, much else left unresolved. We hope this paper can at least emphasize the clear necessity to resolve the climate change problem by countries’ strategic participation in climate coalition to increase its own welfare considering inter-fossil fuel effect.

From the methodology part, still many limitations exist in this paper:

Mainly mathematical models of game theory and numerical models are used to support our analysis, e.g. in our numerical model, we only pick up certain elasticities and presented the results under each value but we couldn’t prove the results within this ranges. However, ideally, the mathematical model should be solved while the parameters remain in the model without any numerical settings which can enable a more thorough analysis. We can even derive conclusions regarding a complete parameter range and further conduct robust test or sensitivity test.

Besides, numerical models could also be further calibrated by econometric methods. For example, by fitting model into a real case between three different energy concentration countries, which may also be inspiring to derive relative conclusions.

Finally, linear demand function is rather simplistic to model the real fossil fuel market. Empirical results used the similar linear regression model can be dated back to almost 1960s, which may harm the explanatory power of our model. It would be useful to adjust the demand function to better fit the market.

8 Abbreviations:

IEA: International Environment Agreement

NE: Nash Equilibrium

CO_2: Carbon Dioxide

GHG: Greenhouse Gas Emissions

IPCC: The Intergovernmental Panel on Climate Change

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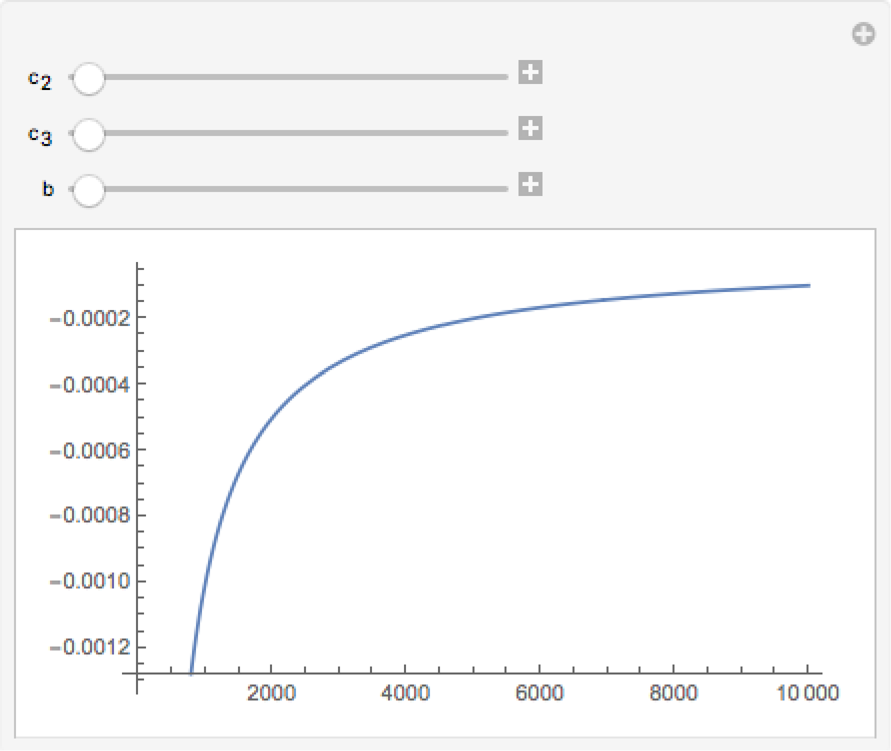
10 Appendix:

1. Calculated expression of τ_1^p in the scenario where no coalition is formed

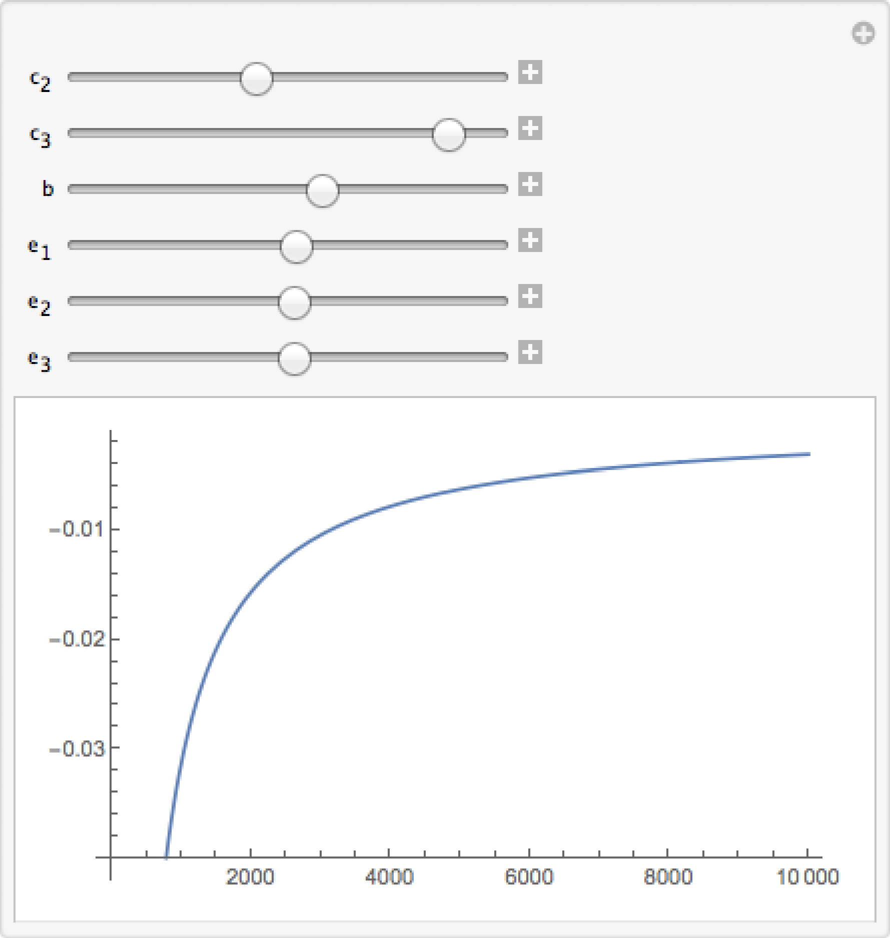
$$
\begin{aligned}
\tau_1^p = (&-\frac{3abc_2^2c_3^2}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2}-\frac{3ac_1c_2^2c_3^2}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2}\\
&-\frac{ac_2c_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\\
&+\left(\frac{\left(-1-\frac{bc_2c_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\right)e_1}{c_1}\right.\\
&-\frac{bc_2e_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\\
&\left.-\frac{bc_3e_2}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\right)\delta_1\\
&-\frac{b^2c_2c_3^2\tau_2^p}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2}\\
&-\frac{bc_1c_2c_3^2\tau_2^p}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2}\\
&-\frac{b^2c_3c_2^2\tau_3^p}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_3c_3)^2}\\
&-\frac{bc_1c_3c_2^2\tau_3^p}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2})\\
&/\ (\frac{bc_2^2c_3^2}{(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2}\\
&+\frac{b^2c_2^2c_3^2}{c_1(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)^2}\\
&+\frac{bc_2c_3}{c_1(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)}\\
&+\frac{\left(-1-\frac{bc_2c_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\right)}{c_1})
\end{aligned}
$$

2. **Result 1:** Parameters and variables within certain range: $\{c_1,0.1,10000\},\{c_2,0.1,100\},\{c_3,0.1,100\},\{b,0.1,100\},\{e_1,0.1,100\},\{e_2,0.1,100\},\{e_3,0.1,100\}$

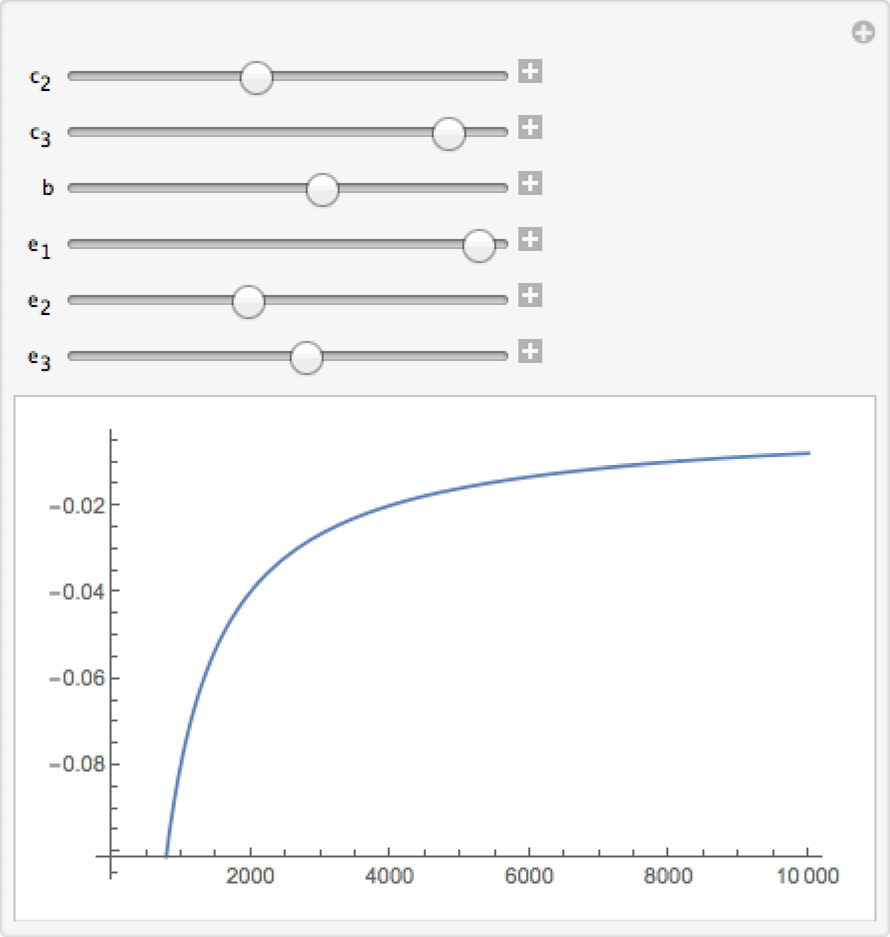
   1 F_1 always stays negative when the other parameters are positive.



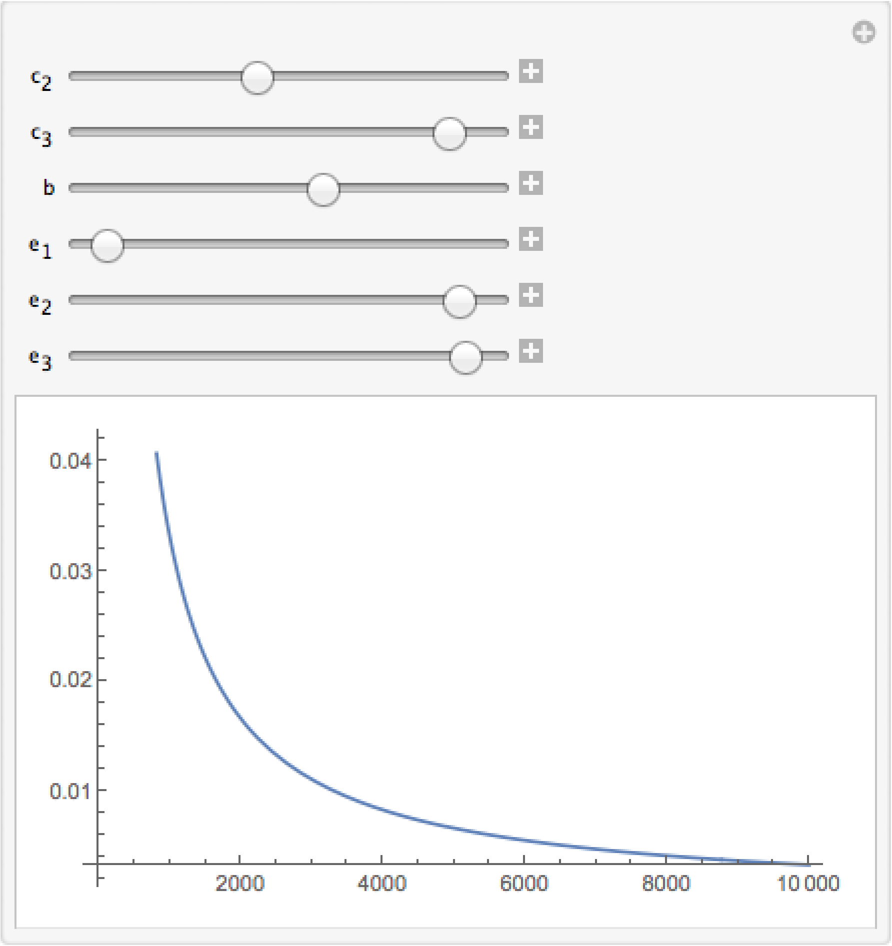
2.1 When e_i is almost the same within different countries, B_1 is negative (shown in graph), B_1/F_1 is positive.



2.2 When e_1 is significantly larger than emission intensity in other two countries, B_1 is negative (shown in graph), B_1/F_1 is positive.



2.3 When e_1 is quite small and emission intensity in other two countries are significantly larger than it, B_1 is positive (shown in graph), B_1/F_1 is negative.



3. Calculated expression of τ_1^p in the scenario where country 1 and country 2 join a coalition leaving country 3 alone

$$\tau_1^p$$

$$= (-\frac{3abc_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} - \frac{6ac_1c_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$- \frac{2ac_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} - \frac{3ac_2c_3\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$+ \frac{3ac_1c_2c_3\left(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}\right)}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$+ \Biggl(\frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)e_1}{c_1} - \frac{bc_2e_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$- \frac{bc_3e_2}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\Biggr)(\delta_1 + \delta_2) - \frac{b^2c_2c_3^2\tau_2^p}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$- \frac{2bc_1c_2c_3^2\tau_2^p}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$- \frac{bc_3\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)\tau_2^p}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$+ \frac{bc_1c_3\left(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}\right)\tau_2^p}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$- \frac{b^2c_3c_2^2\tau_3^p}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_3c_3)^2} - \frac{2bc_1c_3c_2^2\tau_3^p}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

$$- \frac{bc_2\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)\tau_3^p}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}$$

$$+ \frac{bc_1c_2\left(-\frac{bc_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}\right)\tau_3^p}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3})$$

$$/ (\frac{2bc_2^2c_3^2}{(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2} + \frac{b^2c_2^2c_3^2}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)^2}$$

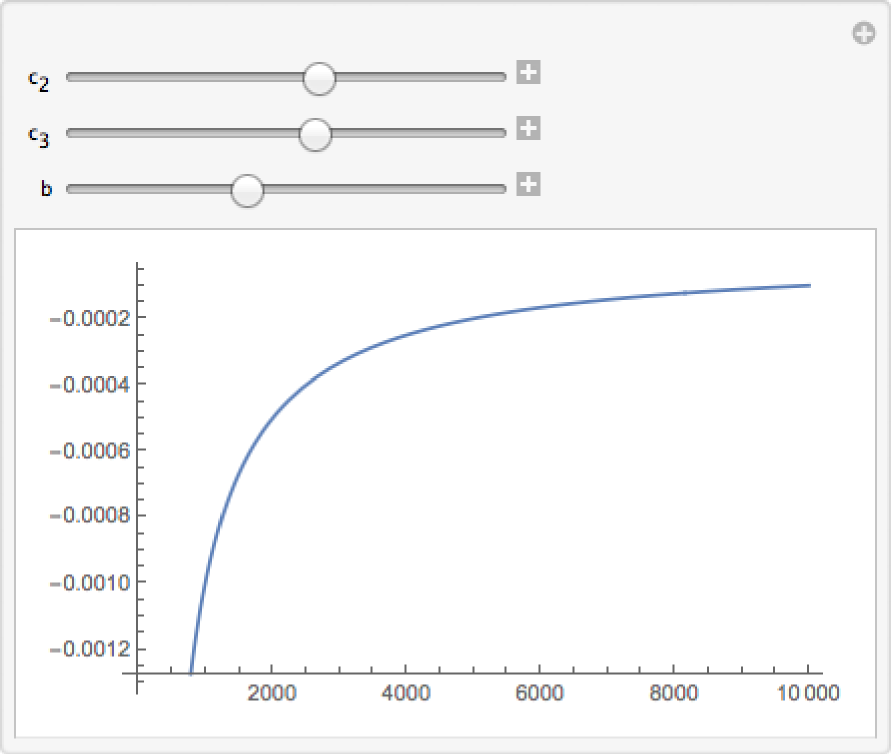
$$+ \frac{bc_2c_3}{c_1(-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3)} + \frac{\left(-1 - \frac{bc_2c_3}{-bc_1c_2 - bc_1c_3 - bc_2c_3 - 3c_1c_2c_3}\right)}{c_1}$$

$$+\frac{bc_2c_3\left(-1-\frac{bc_2c_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\right)}{c_1(-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3)}$$

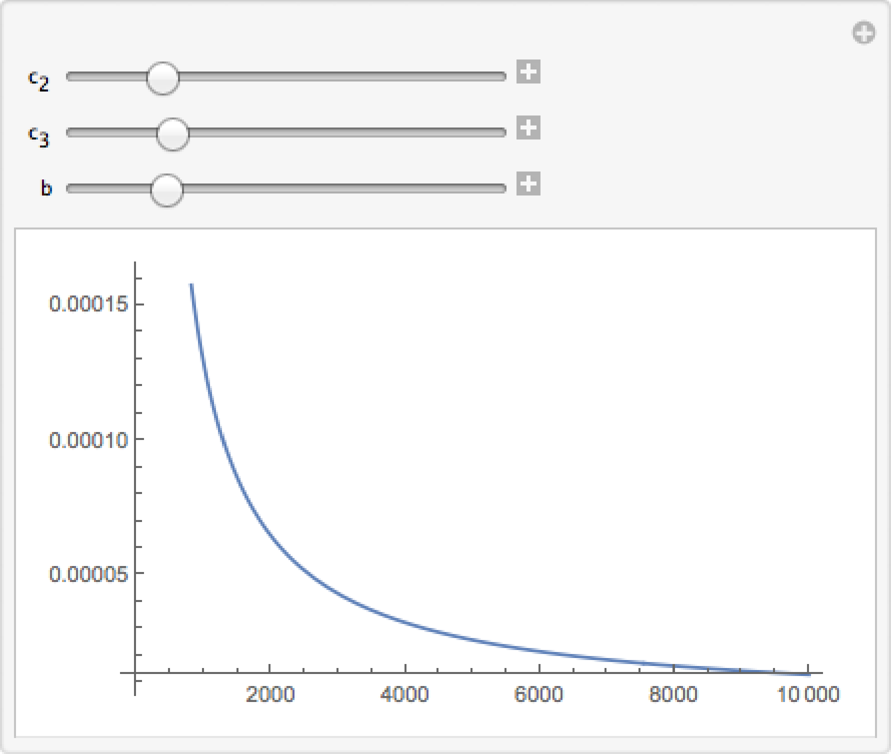
$$-\frac{bc_3c_2\left(-\frac{bc_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}+\frac{\left(-1-\frac{bc_2c_3}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3}\right)}{c_1}\right)}{-bc_1c_2-bc_1c_3-bc_2c_3-3c_1c_2c_3})$$

4. **Result 2:** Parameters and variables within certain range: $\{c_1,0.1,10000\},\{c_2,0.1,100\},\{c_3,0.1,100\},\{b,0.1,100\},\{e_1,0.1,100\},\{e_2,0.1,100\},\{e_3,0.1,100\}$

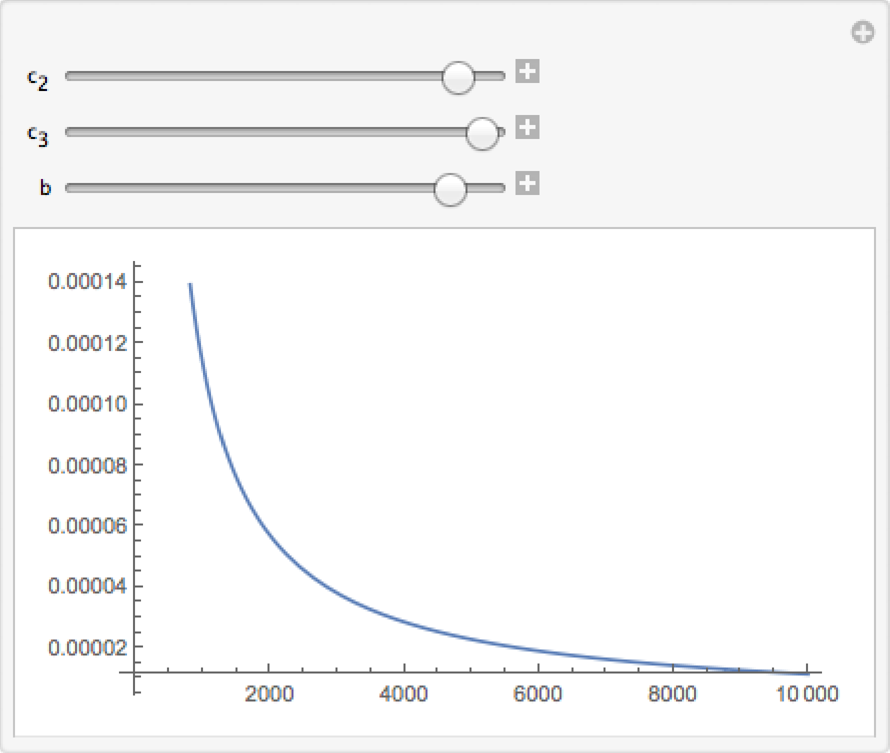
1 $\widetilde{F_1}$ always stays negative when the other parameters are positive.



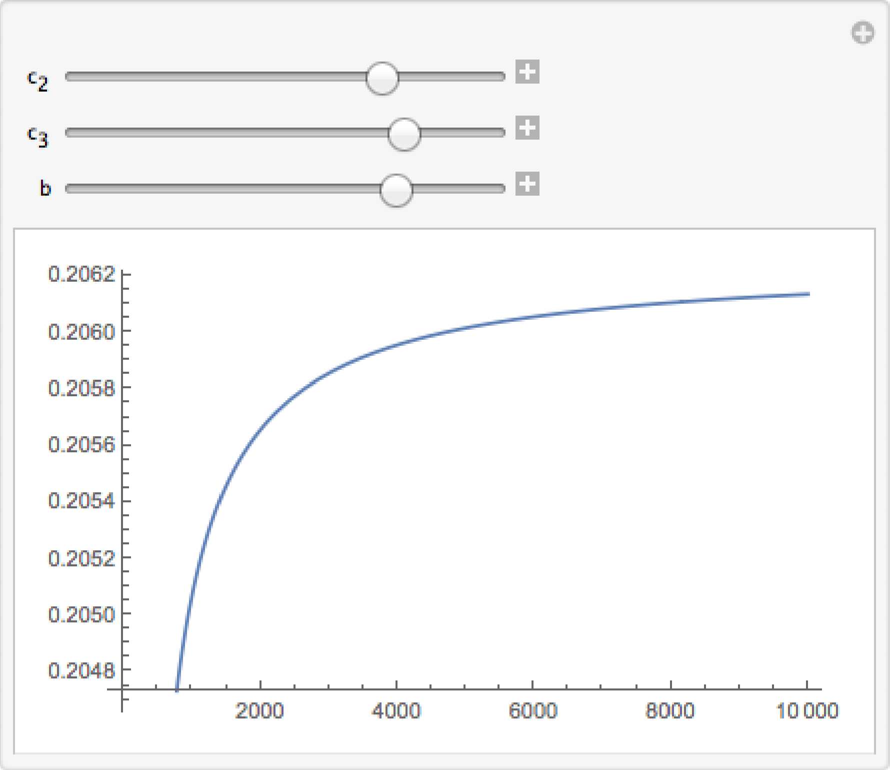
$\widetilde{D_{23}}$ always stays positive when the other parameters are positive.



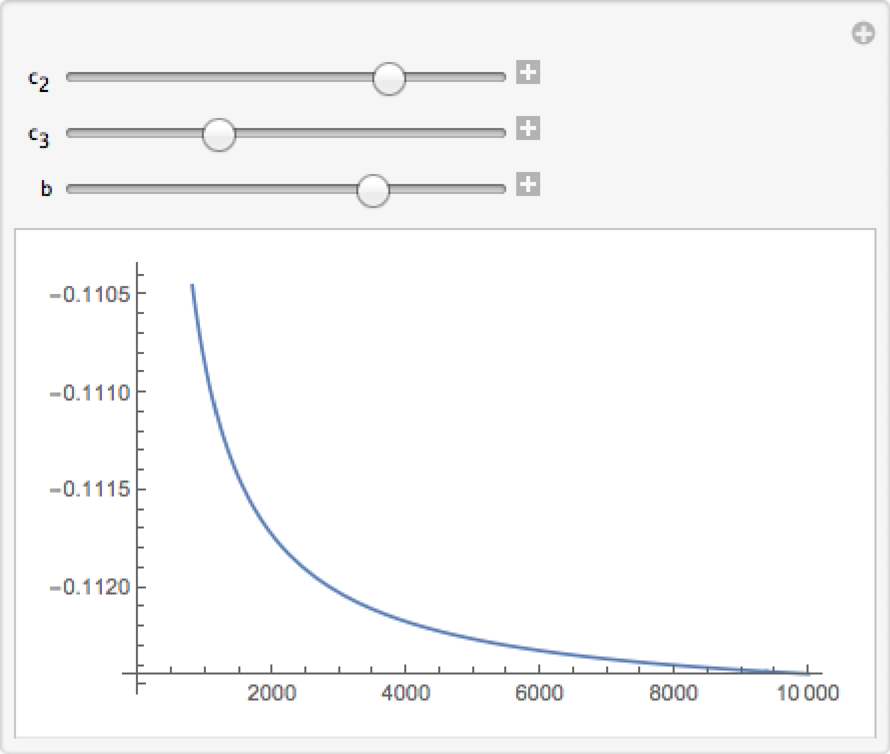
$\widetilde{D_{32}}$ always stays positive when the other parameters are positive.



$\frac{\widetilde{D_{23}}}{\widetilde{F_1}} - \frac{D_{23}}{F_1}$ always stays positive when the other parameters are positive.



$\frac{\widetilde{D_{32}}}{\widetilde{F_1}} - \frac{D_{32}}{F_1}$ always stays negative when the other parameters are positive.



2.1, 2.3, 2.3 is the same with appendix 2 since $\widetilde{B_1} = B_1$

5. **Proof for proposition 1:**

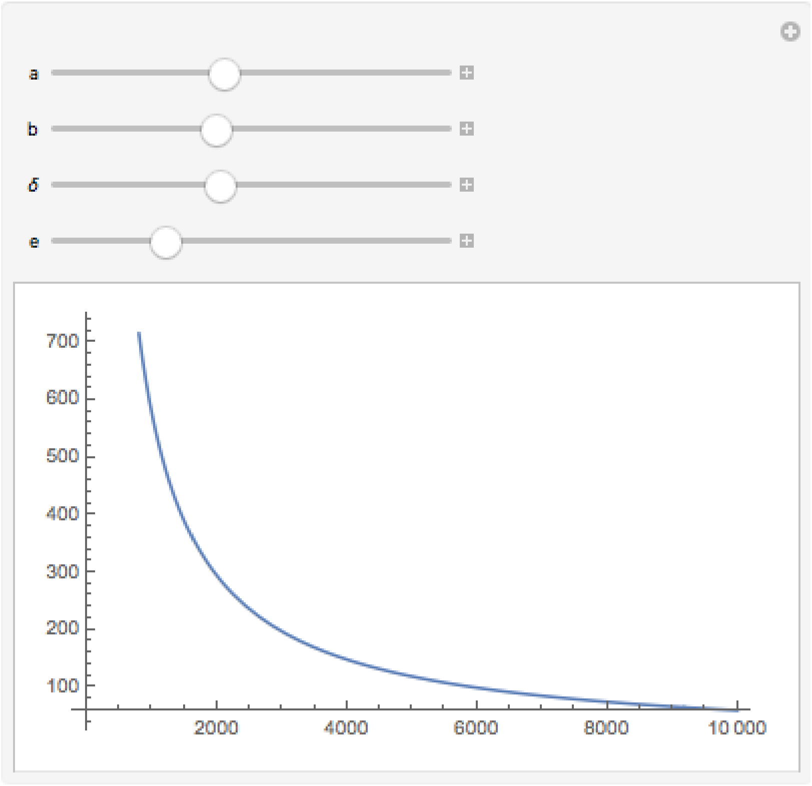
$$(14) - (17) = \frac{3ce\delta}{2b + 3c} - \frac{2(7bce\delta + 9c^2e\delta)}{(b + c)(4b + 9c)} = \frac{ce\delta(-16b^2 - 27c^2 - 29bc)}{(2b + 3c)(b + c)(4b + 9c)} < 0$$

$$(17) - (16) = \frac{2(7bce\delta + 9c^2e\delta)}{(b + c)(4b + 9c)} - \frac{2(10bce\delta + 9c^2e\delta)}{(b + c)(4b + 9c)} = \frac{-6bce\delta}{(b + c)(4b + 9c)} < 0$$

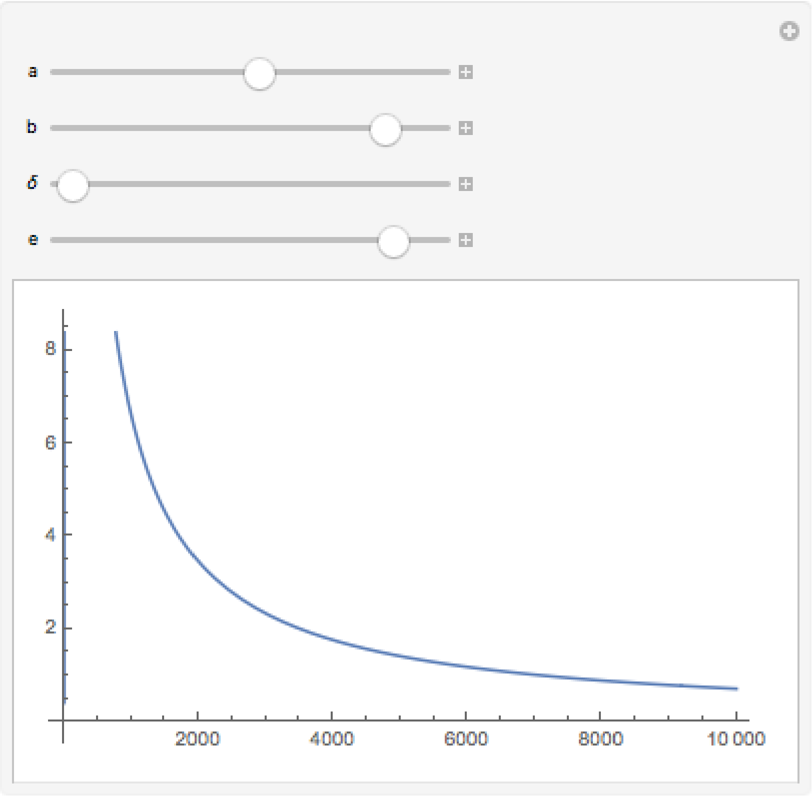
$$(16) - (20) = \frac{2(10bce\delta + 9c^2e\delta)}{(b + c)(4b + 9c)} - 3e\delta = \frac{-e\delta(19bc + 9c^2 + 12b^2)}{(b + c)(4b + 9c)} < 0$$

6. **Graph for the comparison:**

6.1 $W_{\text{grand coalition}} - W_{\text{country outside small coalition}} < 0$



6.2 $W_{\text{country within small coalition}} - W_{\text{individual country}} < 0$



6.3

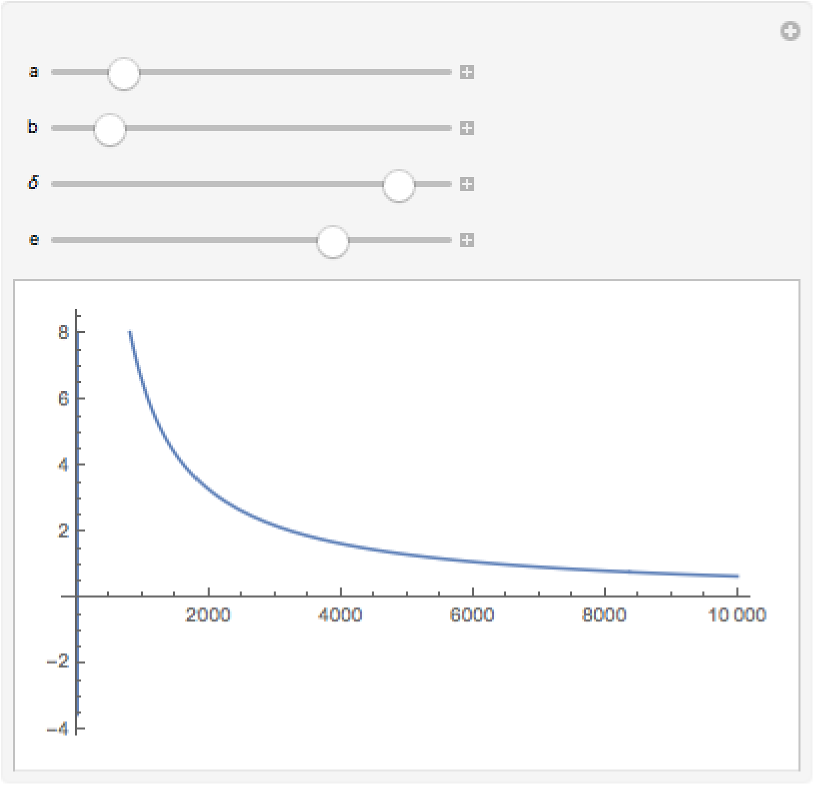
$$W_{\text{country within small coalition}} - W_{\text{country outside small coalition}}$$

$$= \frac{a^2(b+c) - 6a(b+c)e\delta + \dfrac{4c(89b^2 + 252bc + 162c^2)e^2\delta^2}{(4b+9c)^2}}{2(b+c)^2}$$

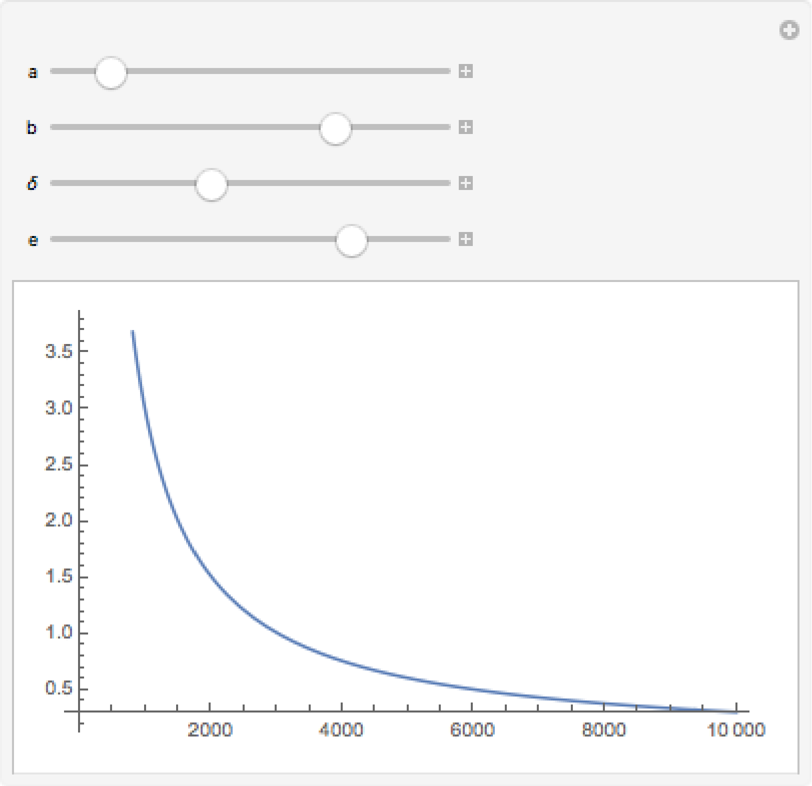
$$- \frac{a^2(b+c) - 6a(b+c)e\delta + \dfrac{8c(70b^2 + 153bc + 81c^2)e^2\delta^2}{(4b+9c)^2}}{2(b+c)^2}$$

$$= \frac{-\dfrac{c(204b^2 + 216bc)e^2\delta^2}{(4b+9c)^2}}{2(b+c)^2} < 0$$

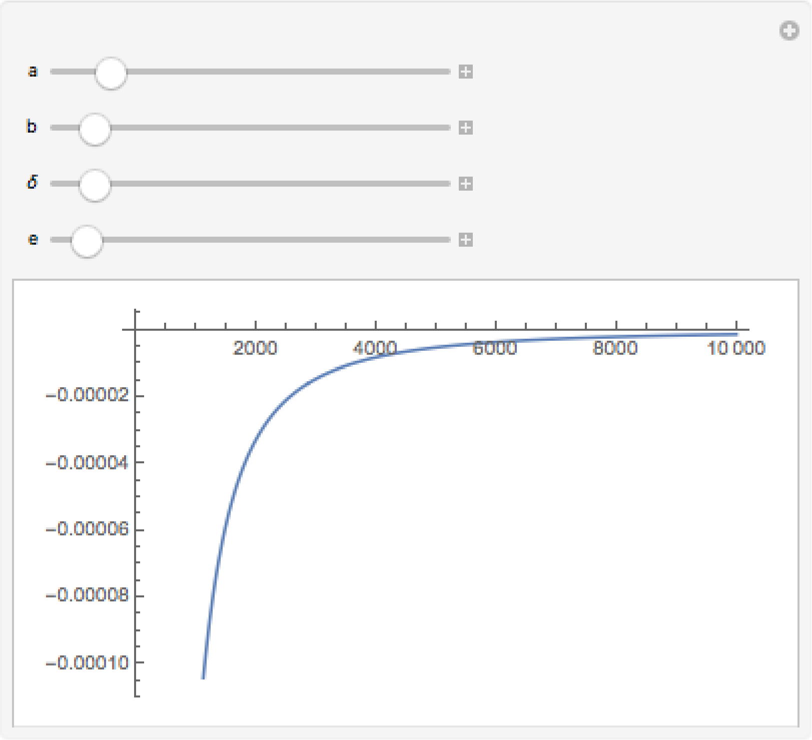
6.4 $q_{\text{individual country}} - q_{\text{country outside small coalition}} > 0$



6.5 $q_{\text{country within small coalition}} > q_{\text{grand coalition}}$



6.6 $q_{\text{country within small coalition}} - q_{\text{country outside small coalition}} < 0$



7. Simulation results where elasticity = 1 and elasticity = 1.75

Table 8 Simulation Result of Elasticity = 1

	S1: Individual Country	S2: Grand Coalition	S3: 1,2 Small Coalition	S4: 1,3 Small Coalition	S5:1 2,3 Small Coalition
Tax country 1	7.69	17.33	11.91	12.83	7.71
Tax country 2	2.21	11.87	8.27	2.33	5.32
Tax country 3	2.14	9.09	2.23	7.33	3.46
Price	92.41	93.13	92.69	92.77	92.47
Supply Quantity country 1	13.84	12.39	13.20	13.06	13.85
Supply Quantity country 2	3.09	2.79	2.90	3.10	2.99
Supply Quantity country3	5.83	5.43	5.84	5.52	5.75
Welfare 1	611.76	608.63	611.60	611.36	612.81
Welfare 1-pollution	-109.90	-99.04	-105.43	-104.48	-109.27
Welfare 1-social surplus	721.66	707.67	717.03	715.84	722.08
Welfare 1-social surplus-producer	692.86	684.09	690.29	689.71	693.74
Welfare 1-social surplus-consumer	28.80	23.58	26.74	26.12	28.35
Welfare 2	65.25	70.85	67.45	69.13	65.21
Welfare 2-pollution	-109.90	-99.04	-105.43	-104.48	-109.27
Welfare 2-social surplus	175.14	169.89	172.87	173.61	174.48
Welfare 2-social surplus-producer	146.35	146.31	146.14	147.48	146.13
Welfare 2-social surplus-consumer	28.80	23.58	26.74	26.12	28.35
Welfare 3	194.59	202.03	198.64	197.90	194.88
Welfare 3-pollution	-109.90	-99.04	-105.43	-104.48	-109.27
Welfare 3-social surplus	304.48	301.07	304.06	302.38	304.15
Welfare 3-social surplus-producer	275.68	277.49	277.32	276.26	275.80
Welfare 3-social surplus-consumer	28.80	23.58	26.74	26.12	28.35
Global emission	7.33	6.60	7.03	6.97	7.28

Table 9 **Simulation Result of Elasticity = 1.75**

	S1: Individual Country	S2: Grand Coalition	S3: 1,2 Small Coalition	S4: 1,3 Small Coalition	S5: 2,3 Small Coalition
Tax country 1	6.95	17.33	11.78	12.32	6.96
Tax country 2	2.89	11.87	8.14	2.96	6.34
Tax country 3	2.49	9.09	2.54	6.83	4.48
Price	95.49	95.94	95.67	95.71	95.55
Supply Quantity country 1	14.47	12.84	13.71	13.62	14.26
Supply Quantity country 2	3.18	2.88	3.00	3.18	3.12
Supply Quantity country3	6.01	5.61	6.02	5.74	6.00
Welfare 1	644.48	639.22	643.55	643.35	644.71
Welfare 1-pollution	-114.37	-102.62	-109.31	-108.70	-112.93
Welfare 1-social surplus	758.85	741.84	752.86	752.06	757.64
Welfare 1-social surplus-producer	741.09	727.39	736.46	735.92	740.29
Welfare 1-social surplus-consumer	17.76	14.45	16.40	16.14	17.35
Welfare 2	59.61	67.23	62.89	64.34	60.60
Welfare 2-pollution	-114.37	-102.62	-109.31	-108.70	-112.93
Welfare 2-social surplus	173.98	169.85	172.21	173.04	173.53
Welfare 2-social surplus-producer	156.22	155.40	155.81	156.91	156.18
Welfare 2-social surplus-consumer	17.76	14.45	16.40	16.14	17.35
Welfare 3	197.74	206.45	202.51	201.78	199.05
Welfare 3-pollution	-114.37	-102.62	-109.31	-108.70	-112.93
Welfare 3-social surplus	312.11	309.06	311.83	310.48	311.98
Welfare 3-social surplus-producer	294.35	294.61	295.43	294.35	294.63
Welfare 3-social surplus-consumer	17.76	14.45	16.40	16.14	17.35
Global emission	7.62	6.84	7.29	7.25	7.53

I hereby declare that the present thesis has not been submitted as a part of any other examination procedure and has been independently written. All passages, including those from the internet, which were used directly or in modified form, especially those sources using text, graphs, charts or pictures, are indicated as such. I realize that an infringement of these principles which would amount to either an attempt of deception or deceit will lead to the institution of proceedings against myself.

Date: Signature: